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CHARLES D. WALCOTT, DIRECTOR

THE

CRYSTAL FALLS IRON-BEARING DISTRICT OF MICHIGAN

BY

J. MORGAN CLEMENTS AND HENRY LLOYD SMYTH

WITH

A CHAPTER ON THE STURGEON RIVER TONGUE

BY

WILLIAM SHIRLEY BAYLEY

AND

AN INTRODUCTION

BY

CHARLES RICHARD VAN HISE

WASHINGTON

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Department of the Interior,
United States Geological Survey,
Washington, D. C., April 23, 1898.

Sir: I transmit herewith the manuscript and illustrations of a monograph upon the Crystal Falls Iron-bearing District of Michigan, by J. Morgan Clements and H. L. Smyth. The district is thus called from its principal mining town. The area reported upon connects the Marquette district on the north and the Menominee district on the south.

This monograph is one of the series which is to treat of the iron-bearing districts of the Lake Superior region. The first of the series was that on the Penokee district (Monograph XIX); the second of the series was that on the Marquette district (Monograph XXVIII). The present report is the third of the series, and the report upon the Menominee district, now being prepared by W. S. Bayley, will be the fourth.

No previous detailed report has been issued upon the Crystal Falls district, although the area has been touched upon by Messrs. T. B. Brooks and Carl Rominger. The present report is the first which contains geological maps and sections of the district.

The field work upon which the present report is based began about five years ago. The work of the first season was a topographical survey and a reconnaissance geological survey. The work of the second season was detail geological work by H. L. Smyth, W. N. Merriam, and their assistants. The work of these two seasons was done for private parties. These parties turned over to me the original specimens, notes, and maps to assist in the preparation of this report. The detail geological mapping of the second year had covered only a part of the area included within the present report, and in the remainder of the area in the following years detail surveys were made by J. Morgan Clements and W. S. Bayley.

In the vicinity of the mines and the iron-bearing formations the examination of the district has been of the most detailed character, practically all of the ledges having been visited and advantage having been taken of underground workings and borings. Moreover, in order to determine the succession, for large areas, it was necessary to make a close magnetic survey with the dial compass and dip needle. In the areas more remote from the mines the work was of a less detailed character.

The western half of the district is treated by J. Morgan Clements in Part I of this monograph. The eastern half of the district, with the exception of the Sturgeon River tongue, is treated by H. L. Smyth in Part II. The chapter upon the Sturgeon River tongue was prepared by W. S. Bayley. My own part of the work has been a general supervision of the entire survey, with frequent trips into the region to assist in solving the general structural problems.

To the gentlemen who furnished the complete results of their surveys for the first two seasons, we are deeply indebted. The drawing for the maps was done by E. C. Bebb. The colored plates were prepared by J. L. Ridgway.

Very respectfully, your obedient servant,

C. R. Van Hise,
Geologist in Charge.

Hon. Charles D. Walcott,
Director United States Geological Survey.

INTRODUCTION.

By C. R. Van Hise

This report is a full account of the Crystal Falls iron-bearing district of Michigan.

The rocks of the district comprise two groups, separated by unconformities. These are the Archean and the Algonkian. The Algonkian includes both the Lower Huronian and the Upper Huronian series, and these are also separated by unconformities. The terms Lower Huronian and Upper Huronian are applied to the series which occur in this district because they are believed to belong to the same geological province as the Huronian rocks of the north shore of Lake Huron, and to be equivalent to the Lower Huronian and Upper Huronian series which there occur. The reasons for this belief are fully given in Bulletin 86.[1]

The Archean is believed to be wholly an igneous group, and therefore no estimate of its thickness can be given. It covers a broad area in the eastern part of the district, and from this several arms project west. West of the main area there are two large oval areas of Archean.

The Lower Huronian series, from the base upward, comprises the Sturgeon quartzite, from 100 feet to more than 1,000 feet thick; the Randville dolomite, from 500 feet to 1,500 feet thick; the Mansfield slate, from 100 feet to 1,900 feet thick; the Hemlock volcanic formation, from 1,000 feet to 10,000 or more feet thick; and the Groveland formation, about 500 feet thick. We thus have a minimum thickness for the series of about 2,200 feet, and a possible maximum thickness of more than 16,000 feet. However,

[1] Correlation papers, Archean and Algonkian, by C. R. Van Hise: Bull. U. S. Geol. Survey No. 86, 1892, pp. 156–199.

a large part of the latter is composed of volcanic material. It is not likely that the sediments at any one place are as much as 5,000 feet thick.

The Upper Huronian is a great slate and schist series, which it is not possible to separate on the maps into individual formations, and it is impossible to give even an approximate estimate of the thickness of this series.

Various igneous rocks intrude in an intricate manner both the Upper Huronian and the Lower Huronian series.

The aim of the following paragraphs is to sketch very briefly the history of the district.

THE ARCHEAN.

The Archean consists mainly of massive and schistose granites and of gneisses. Nowhere in the Archean have any rocks of sedimentary origin been discovered. The Archean has been cut by various igneous rocks, both basic and acid, at different epochs. These occur in the form both of bosses and of dikes, the latter sometimes cutting, but more ordinarily showing a parallelism to, the foliation of the schistose granites. The granites must have formed far below the surface, and therefore must have been deeply denuded before the transgression of the Lower Huronian sea. The Archean granites and gneisses and the earlier intrusives alike have been profoundly metamorphosed, and at various places have been completely recrystallized.

THE LOWER HURONIAN SERIES.

The Sturgeon quartzite, the first deposit of the advancing sea, when formed consisted mainly of sandstone, but in places at the base of coarse conglomerate. The conglomerate is best seen in the Sturgeon River tongue. Elsewhere evidence of conglomeratic character at the base of the formation is seen, but the metamorphism has been so great as nearly to destroy the pebbles. However, in the Sturgeon River tongue is a great schistose conglomerate, which, while profoundly metamorphosed, still gives evidence of the derivation of its material from the older Archean rocks. The sandstone has been changed to a vitreous, largely recrystallized quartzite, which now shows only here and there vague evidence of its clastic character.

The Sturgeon formation varies from probably more than 1,000 feet in

thickness in the Sturgeon River tongue to less than 100 feet in thickness at places in the Felch Mountain range, and is altogether absent in the northeastern part of the district.

In the southeastern part of the district the Sturgeon quartzite is overlain by the Randville dolomite. In the central part of the district the quartzite between the Archean and the Randville is so thin that it can not be represented on the maps as a separate formation. In the northeastern part of the district a quartzite resting on the Archean, but occupying a higher position stratigraphically than the Randville dolomite, is overlain by an iron-bearing formation. It appears, therefore, that the Sturgeon sea gradually overrode the district, and that at the time the Sturgeon quartzite was deposited in the southeastern part of the area, the Archean was not yet submerged in the central and northeastern parts of the district. However, since the quartzite resting on the Archean in the latter area can not be separated lithologically from the Sturgeon quartzite, both are given the same formation color, but the later quartzite is given a separate letter symbol. The quartzite color therefore represents a transgression deposit of the same general lithological character, rather than a formation, all parts of which have exactly the same age. While nowhere in the district is there any marked discordance between the schistosity of the Archean and the Sturgeon quartzite, the conglomerates at the base of the latter formation in the Sturgeon River tongue are believed to indicate a great unconformity between the Archean and the Lower Huronian series. The change from the Sturgeon deposits to those of the Randville was a transition.

The Randville dolomite is a nonclastic sediment, and is believed to mark a period of subsidence and transgression of the sea to the northeast, resulting in deeper waters for much of the district. Since the Randville dolomite has its full thickness on the Fence River just east of the western Archean oval, and does not appear at all about the Archean oval a short distance to the northeast, it is probable that the shore line, during Randville time, was between these two areas and that the land arose somewhat abruptly toward the northeast. As the Randville formation has a thickness of 1,500 feet, it probably represents a considerable part of Lower Huronian time.

Following the deposition of the Randville dolomite, deposits of very different character occur in different parts of the district. These deposits

are: (1) The Mansfield formation, (2) the Hemlock volcanic formation, and (3) the Groveland formation.

The Mansfield formation was a mudstone, which has subsequently been transformed into a slate or schist. The Hemlock formation is mainly a great volcanic mass, including both basic and acid rocks, lavas, and tuffs, but it contains also subordinate interbedded sedimentary rocks. This formation occupies a larger area than any other of the Lower Huronian formations and is perhaps the most characteristic feature of the Crystal Falls district. The Groveland is the iron-bearing formation. It includes sideritic rocks, cherts, jaspilites, iron ores, and other varieties characteristic of the iron-bearing formations of the Lake Superior region. In all important respects these rocks are similar to those of the Negaunee formation of the Marquette district, with the exception that in the southeastern part of the Crystal Falls district, associated with the nonclastic material, there is a considerable proportion of clastic deposits. The Groveland formation contains iron carbonate and possibly glauconite, from which its other characteristic rocks were derived.

The variability in the character of the deposits overlying the Randville formation is probably caused by the great volcanic outbreaks in the western part of the district. In the southern and southeastern parts of the area the deposit overlying the Randville formation is the Mansfield slate and schist. North of Michigamme Mountain and of the Mansfield area the Mansfield formation is replaced along the strike by the Hemlock volcanic formation, which directly overlies the limestone for most of the way about the western Archean oval. The effect of the volcanic outbreak apparently did not reach so far as the northeastern part of the district.

Overlying the Mansfield formation in the southeastern part of the district and the Randville formation in the central part of the district is the Groveland iron-bearing formation. In the Mansfield slate area the iron-bearing rocks appear near the top of the Mansfield formation intercalated with the slates. The Groveland formation can not be certainly traced farther north than the northeastern portion of the western Archean oval. It is apparently replaced along the strike by the Hemlock volcanics.

In the northeastern part of the district the Groveland formation, equivalent to the Negaunee formation of the Marquette district of Michigan,

is found above the Ajibik formation. The occupation, in the western part of the district, by the Hemlock volcanics of the same part of the geological column as the Hemlock volcanics east of the western Archean oval, the Mansfield slate, and the Groveland formation, is explained by the fact that in the western part of the district the volcanoes first broke out and there continued their activity longest. While north of Crystal Falls the volcanic rocks were being laid down, the Mansfield formation was being deposited in the southeastern part of the district. This activity continued there through the time that the Groveland formation was being deposited in other parts of the district.

From the foregoing it appears that the Hemlock formation in the western part of the district is equivalent:

(1) East of the western Archean oval, to the Hemlock volcanics found there and the overlying Groveland formation;

(2) At Michigamme Mountain, to the Mansfield slates and the Groveland formation;

(3) In the Mansfield area, to the Mansfield slates and the Hemlock volcanics occurring there; and

(4) In the southeastern part of the district, to the Mansfield and Groveland formations.

The replacement of an iron-bearing formation by the great volcanic formation just described is exactly paralleled in the Upper Huronian rocks of the Penokee iron-bearing series, where the pure iron-bearing formation is replaced at the east end of the district by a great volume of volcanic rocks intercalated with slates and containing bunches of iron-formation material.[1]

Following the deposition of the Lower Huronian series the region was raised above the sea and eroded to different depths in different places. In the Felch Mountain range the only formations above the Randville dolomite are a thin bed of slate and the Groveland iron formation. In the northeastern part of the district only a thin belt of iron-formation rocks remains. In the central and western parts of the district there is a great thickness of volcanics. This, however, does not imply a difference of erosion equal to

[1] The Penokee iron-bearing district of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey, Vol. XIX, 1892, pp. 428–433.

the difference in thickness of these rocks, for doubtless when the volcanics were built up there was contemporaneous subsidence, so that at the end of Lower Huronian time there may have been little variation in the elevation of the upper surface of the series, but very great difference in its thickness.

THE UPPER HURONIAN.

After the Lower Huronian series was deposited the district was raised above the sea, may have been gently folded, and was eroded to different depths in different parts of the district.

Following the earth movements and erosion the waters for some reason advanced over the district and the Upper Huronian series was deposited. The basal horizon was a conglomerate, which has, however, very different characters in different parts of the district.

In the eastern half were Archean rocks, the Sturgeon quartzite, the Mansfield slate, and the Groveland iron formation. Upon these was deposited a sandstone which locally was very ferruginous. This has subsequently been changed into a ferruginous quartzite. The typical occurrence of this quartzite is at the east end of the Felch Mountain range. It also appears between the Archean ovals in the northeastern part of the district. If distinct conglomerates were formed at the bottom of this quartzite, they are buried under glacial deposits or have disappeared as the result of metamorphism.

In the western part of the district the rocks of the Lower Huronian at the surface are the great Hemlock formation, and here the basal horizon of the Upper Huronian is a slate or slate conglomerate, the fragments of which are derived mainly from the underlying Hemlock formation. The sandstones and conglomerates varied upward into shales and grits, which have been subsequently altered into mica-slates and mica-schists. After a considerable thickness of mudstone and grit was deposited, there followed a layer of combined clastic and nonclastic sediments, the latter including iron-bearing carbonates. These appear to be at a somewhat persistent horizon, and in this belt are found the iron-formation rocks, and iron ores in the Upper Huronian in the vicinity of Crystal Falls. Above these ferruginous rocks there was deposited a great thickness of shales and grits, which have been transformed into mica-slates and mica-schists.

FOLDING OF THE ARCHEAN AND HURONIAN SERIES.

The Crystal Falls district had now been an area of deposition for a very long time, and a great thickness of sediments had accumulated. A profound physical revolution next occurred, the greatest since Archean time. The region was raised above the sea and was folded in a most complex manner. As a consequence, the more conspicuous folds vary from a north-south to an east-west direction. The closer folds in the northeastern part of the area are nearly north-south. In the central part of the area the closer folds strike northwest-southeast. In the eastern and southeastern parts of the district the closer folds are nearly east-west. All of these folds, however, have steep pitches. It therefore follows that the region was subjected to great compressive stresses in all directions tangential to the surface of the earth, and that the yielding was mainly in one direction here and in another there, although on every fold there is evidence of yielding in two directions at right angles to each other. Some of the folds are very close, as in the case of the Huronian area between the two Archean ovals in the northeastern part of the district, and in the Felch Mountain range. In other areas—as, for instance, in the Crystal Falls syncline—the major fold is somewhat open. However, upon the open folds are superimposed folds of a higher order, so that the detail structure is very complicated. So far as known, the district has nowhere been faulted.

Subsequent to or during the late stage of this time of folding there was a period of great igneous activity, probably contemporaneous with the Keweenawan. At this time there were introduced into both the Lower and the Upper Huronian rocks vast bosses and numerous dikes. The intrusives vary from those of an ultrabasic character, such as peridotites, through those of a basic character, such as gabbros and dolerites, to those of an acid character, such as granites. These intrusives, while altered by metasomatic changes, do not show marked evidence of dynamic metamorphism—therefore the conclusion that they were introduced later than the period of intense folding, already described.

A few illustrations are mentioned. The Archean and other great massifs are less profoundly altered than are the softer and weaker deposits of the Huronian. In these more rigid formations, such as the granites and quartzites, all phases of alteration by granulation and recrystallization are

beautifully exhibited. The Sturgeon River area affords one of the best-known illustrations of a schistose conglomerate the matrix of which has completely recrystallized and, therefore, can not be discriminated from a gneiss of igneous origin, but contains numerous pebbles and bowlders flattened in the plane of schistosity.

The great Hemlock volcanic formation varies from rocks which are altered chiefly by metasomatic change to those which have become complete crystalline schists containing no vestige, either macroscopically or microscopically, of a texture or structure which may be interpreted as igneous.

SUBSEQUENT HISTORY.

After the introduction of the intrusives the region was subjected to vast denudation, which reduced it approximately to its present configuration. This period of erosion continued until late Cambrian time, when the sea again overrode the district and deposited upon the older rocks Upper Cambrian sediments. Long after the deposition of the Cambrian, and perhaps later Paleozoic rocks, the district was again raised above the sea, and the major part of the Cambrian deposits have been removed, although they are found in patches throughout much of the district, and occur as a continuous sheet just east of the area discussed.

The district may have again been submerged in Cretaceous time; but if so, the deposits formed were removed after the area finally emerged from the sea. Since Cretaceous time the region seems to have been one of erosion. During the Pleistocene period a thick mantle of glacial deposits was spread over the entire district. Since Pleistocene time erosion has advanced far enough to uncover the rocks here and there.

METAMORPHISM.

The folding varied in its closeness in different parts of the district. Moreover, the formations are of very variable character, including a great variety of sediments and of igneous rocks. The formations, therefore, vary greatly in their capacity to resist stresses. It thus follows that during the folding process certain formations yielded to a much greater degree than others. The amount of contained water and other conditions were also variable. As a result of these many variable factors, it is one of the most characteristic features of the district that there are to be found nearly all

varieties of metamorphism in various stages of advancement. The working out of the details of the transformations of the different kinds of rocks during their processes of metamorphism is one of the chief scientific results which has come from a study of the district.

CORRELATION.

In order to compare the succession in the Crystal Falls district with that in the adjacent Marquette and Menominee districts, the descending pre-Cambrian succession in each of the three districts is here given in parallel columns, the formations which are thought to be equivalent being placed opposite one another:

Descending succession of formations in the Marquette, Crystal Falls, and Menominee districts.

MARQUETTE DISTRICT.	CRYSTAL FALLS DISTRICT.	MENOMINEE DISTRICT.
Upper Marquette.	*Upper Huronian.*	*Upper Menominee.*
(1) Michigamme formation, bearing a short distance above its base an iron-bearing horizon, and being replaced in much of the districtby the Clarksburg volcanic formation.	(1) Michigamme formation, bearing a short distance above its base an iron-bearing horizon.	(1) Great Slate formation
(2) Ishpeming formation, being composed of the Goodrich quartzite in the eastern part of the district and of the Goodrich quartzite and the Bijiki schists in the western part of the district.	(2) Quartzite in eastern part of district.	
Unconformity.	*Unconformity.*	*Unconformity.*
Lower Marquette.	*Lower Huronian.*	*Lower Menominee.*
(1) Negaunee iron formation, 1,000 to 1,500 feet.	(1) The Groveland formation, about 500 feet thick.	(1) Vulcan iron formation containing slates.
(2) Siamo slate, in places including interstratified amygdaloids, 200 to 625 feet thick.	(2) Hemlock volcanic formation, 1,000 to 10,000 feet thick. In western part of district also occupies the place of (1) and (3).	
(3) Ajibik quartzite, 700 to 900 feet.		(2) Antoine dolomite.
(4) Wewe slate, 550 to 1,050 feet.	(3) Mansfield formation, 100 to 1,900 feet thick.	
(5) Kona dolomite, 550 to 1,375 feet.	(4) Randville dolomite, 500 to 1,500 feet thick.	
(6) Mesnard quartzite, 100 to 670 feet.	(5) Sturgeon quartzite, 100 to 1,000 feet thick.	(3) Sturgeon quartzite.
Unconformity.	*Unconformity.*	*Unconformity.*
Archean.	*Archean.*	*Archean.*

From the three columns it appears that the equivalents in the different districts can be made out with a considerable degree of certainty. There are, however, various differences, due to several causes.

For Upper Huronian time, omitting the Clarksburg formation, the suc-

cession in the Marquette, Crystal Falls, and Menominee districts is substantially the same. The Clarsksburg formation in the Marquette district may be omitted from consideration, because it is volcanic and replaces in part the Michigamme and Ishpeming formations. The Upper Huronian was a great period of slate and grit deposition. The chief difference which appears between the Menominee district and the other two districts is that in the former no iron ores have been found in the Upper Huronian within the district proper, although such rocks occur a short distance to the west, at Commonwealth and Florence, in Wisconsin.

The succession for the Lower Huronian in the three districts can be paralleled with a high degree of probability. The chief differences are due to the disturbance of the great volcanic outburst in the western part of the Crystal Falls district and to the uneven surface of the Archean land at the beginning of Lower Huronian time. As a consequence of the latter, the waters did not reach the western part of the Marquette district and the northeastern part of the Crystal Falls district as early as the eastern part of the Marquette district, the central part of the Crystal Falls district, and the Menominee district. The transgression of the Lower Huronian sea for the region covered in these three districts was therefore from the southeast toward the northwest.

The Negaunee iron formation of the Marquette district is equivalent to the Groveland iron formation of the Crystal Falls district and the Vulcan iron formation of the Menominee district.

The Siamo slate and the Ajibik quartzite of the Marquette district are approximately equivalent to the Hemlock volcanic formation in much of the Crystal Falls district, but in places where the latter formation displaces the Mansfield formation they are equivalent to only a part of the Hemlock volcanic formation. The Wewe slate of the Marquette district is equivalent in the western part of the Crystal Falls district to a part of the Hemlock volcanic formation, and in the southeastern part of the district is probably equivalent to a part of the Randville dolomite. It appears that the Siamo slate, Ajibik quartzite, and Wewe slate of the Marquette district, and the Mansfield and Hemlock formation of the Crystal Falls district, are equivalent to a part of the Antoine dolomite of the Menominee district.

The great dolomite formation occurring in all of the districts is supposed to be equivalent, except that, as just explained, the deposition of

limestone continued longer in the southeastern part of the Crystal Falls district and in the Menominee district than in the remainder of the region. The absence of the limestone and lower formations in the western two-thirds of the Marquette district and the northeastern part of the Crystal Falls district is explained by the fact that during early Algonkian time this part of the region was not submerged. The Mesnard quartzite of the Marquette district and the Sturgeon quartzite of the Crystal Falls and Menominee districts stand opposite each other.

From the foregoing it is apparent that the three districts together present a most interesting and complex structural problem. While there is sufficient similarity in the formations for one to feel considerable assurance of their general equivalence in the different districts, it is certain that the formations of similar kind did not begin and end at the same time. Moreover, there are remarkable lateral transitions in sedimentation, as a result of the uneven surface of the Archean at the beginning of Algonkian time and because of volcanic outbursts. As a result of the first of these conditions, it is necessary to equate fragmental formations which occur in the central and western parts of the Marquette district and the northeastern part of the Crystal Falls district, with nonfragmental limestones in the area to the east and south. Consequent upon the Upper Huronian volcanic outbursts in the Marquette district, the Michigamme and Ishpeming formations are largely replaced by the Clarksburg volcanics. Similar outbursts in the western part of the Crystal Falls district in Lower Huronian time placed volcanic rocks for this part of the district opposite the Mansfield slate and the Groveland iron formation.

The foregoing relations, combined with the great variety and complexity of the sediments of the district, the presence of many forms of contemporaneous volcanic deposits, the intrusion of the widest variety of igneous rocks of various ages from Archean to later Algonkian time, and the complicated folding and metamorphism to which the district has been subjected, will readily convince one that the working out of the detail structure of the district by Messrs. Clements, Smyth, Bayley, Merriam, and others has not been accomplished without most painstaking and laborious work, especially as the region is covered by timber or brush and is overspread by a mantle of glacial deposits.

OUTLINE OF THIS MONOGRAPH.

PART I.

CHAPTER I. The Crystal Falls district is situated on the Upper Peninsula of Michigan, and forms a connecting link between the Marquette and Menominee districts of Michigan. A history of the previous work in the district, accompanied by a summary of the literature, is given, and there is reproduced a series of maps which indicate the development of knowledge concerning the distribution of the rocks and their structural relations. As explanatory of the locations given, the mode of work is described and the object and method of taking magnetic observations is briefly outlined.

CHAPTER II treats of the geographical limits, structure, stratigraphy, and physiography. The portion of the district here described includes approximately 540 square miles. Structurally it is closely related to the Marquette district; the essential features being a northwest-southeast set of folds, with a superimposed series trending northeast-southwest. The oldest rocks belong to the Archean. They cover an oval area which is surrounded by the Algonkian rocks represented by the Lower and Upper Huronian series. The Archean and Algonkian are overlain with strong unconformity by rocks of the Cambrian division of the Paleozoic. The drift deposits of the Quaternary are everywhere present. Only the pre-Paleozoic rocks, however, are discussed. The most noticeable topography is that of the drift, which in places is seen to be superimposed upon pre-Pleistocene topography. The maximum elevation is 1,900 feet above sea level, and the minimum 1,250 feet. The conclusion is reached that this portion of Michigan before Glacial times had been reduced to the condition of an approximate peneplain. The drainage is chiefly by a few large streams which flow into Green Bay of Lake Michigan. A small part is drained by streams flowing into Lake Superior. In portions of the area the drainage has reached an advanced stage, in other portions it is very youthful. The development of the drainage is illustrated in the case of the Deer River. The timber and soil vary much in character.

CHAPTER III treats of the Archean. The rocks of this age form an elliptical core, following the axis of a northwest-southeast trending anticline. Exposures are few because of the superimposed drift. The Archean is overlain unconformably by Algonkian sediments derived from the granite, and there is absence of contact action. These facts indicate that it was the floor upon which the overlying sediments were deposited. Petrographically it consists chiefly of biotite-granite. On the periphery of the area a biotite gneissoid granite is very well developed. Some of this at least is of dynamic origin. The Archean is cut by acid and basic dikes which are now both schistose and massive.

CHAPTER IV treats of the Lower Huronian series. This series is subdivided into the following formations, from the base upward: The Randville dolomite, the Mansfield slate, and the Hemlock volcanics.

Section I. The Randville dolomite is poorly exposed. It consists of quartzose dolomite, grading down into quartz-schist and recomposed granite. It has evidently been derived partly from the granite, and is considerably younger than that. Its relations to the overlying formations were not observed. The thickness could not here be determined, but, in the area studied by Smyth, its maximum is about 1,500 feet.

Section II. The Mansfield slate is best exposed in the vicinity of the town of the same name. It here occupies a valley, through which flows the Michigamme River. Petrographically this formation includes graywackes, clay slate, phyllite, siderite-slate, chert, ferruginous chert, and iron ores, with various metamorphic products derived from them. The slate predominates. The Mansfield slates are intruded by basic igneous rocks, which underlie them. They are overlain by volcanics, which contain fragments of the slates, and are hence younger than they. The Mansfield slates strike north and south and dip on an average 80° to the west. They represent the limb of a westward-dipping monocline. The maximum thickness of the belt is 1,900 feet. Followed south away from the point of maximum thickness it rapidly thins out and disappears. In the slate but a single ore body of commercial importance has been found. This is exploited by the one Bessemer ore-producing mine of the district. The ore body is presumed to have resulted from the alteration of a siderite, and the concentration in a favorable position of the iron from the portions of the ferruginous beds removed by erosion. A possible continuation of the Mansfield slate is suggested by the occurrence of small outcrops of somewhat similar slates about 5 miles slightly to the west of north.

Section III. The Hemlock formation consists almost exclusively of volcanic rocks, both basic and acid, with crystalline schists derived from them. Sedimentary rocks play a very unimportant rôle. Exposures are numerous west of the belts of previously described rocks, and where erosion has removed the drift the formation has a marked influence on the topography. The thickness is estimated from the dip to reach 23,000 feet, but this is probably illusory because of reduplication due to folding. In the northern portion of the district the formation overlies the Kona dolomite. In the southern portion it overlies conformably the Mansfield slate. It is probable that volcanic activity began in the north and moved south, and that some of the volcanics to the north are contemporaneous with the Mansfield slates. The volcanics are cut by a few acid dikes. Basic dikes forming enormous bosses of basic rock are of frequent occurrence. The volcanic origin of the major portion of this formation is perfectly clear. Some of the volcanics are submarine. The greater proportion, however, were derived from volcanic vents, which could not be located, but were probably situated near the Huronian shore line. The Hemlock volcanics are divided into igneous and sedimentary rocks. Under the igneous rocks there are described both acid and basic lavas and pyroclastics. Under the sedimentary rocks there are described volcanic sediments, both of eolian and water-deposited character. By extreme metamorphism crystalline schists have been produced from both igneous and sedimentary rocks. The acid volcanics include rhyolite-porphyries and aporhyolite-porphyry. The rhyolite-porphyry shows interesting micropoikilitic textural characters. Some of the porphyries have been rendered schistose by pressure. Acid pyroclastics are scarce and were derived from the aporhyolite. The basic lavas correspond to the modern basalts. They are much altered. To indicate these facts and at the same time show their correspondence to the Tertiary and recent basalts, they are called "metabasalts." The basic lavas include nonporphyritic, porphyritic, and variolitic types. A columnar structure was not observed, but an ellipsoidal structure is very common. This structure is described in detail and the conclusion reached that basalts possessing this structure were originally very viscous and correspond to the modern *aa* lavas. The amygdaloidal structure, which is almost universally present in the volcanics, is described and illustrated. The alteration of the basalts is discussed and special cases described. As result of this alteration the textural as well as the mineralogical characters may be completely changed, and the volcanic origin of the resulting rocks could not be determined but for their association. In the zone of weathering, calcification is the controlling alteration process. In rocks more deeply buried, silicification is the process which predominates. The pyroclastics comprise eruptive breccia, including thereunder friction breccias and flow breccias, and volcanic sedimentary rocks. The eolian deposits, which are described as tuffs, grade from fine dust deposits up into those in which the fragments are bowlders. The water-deposited volcanic fragmentals are known as volcanic conglomerates, and likewise grade from those of which the particles are of minute size into those of which the fragments are of very large size. At various places clastic rocks occur which are now schistose, and whose exact mode of origin—that is, whether eolian or water deposited—could not be determined. Normal sediments consisting of slate with limestone

lenses form a lenticular deposit in the volcanics near the top of the formation. They are insignificant in quantity.

Under the Bone Lake crystalline schists there are included rocks of completely crystalline character, but which by field and microscopical study have been connected with the volcanics and are considered to have been derived from rocks similar in nature to them.

The rocks composing the Hemlock formation are little likely, owing to their somber color, to be much used for building or ornamental purposes. They offer, however, an inexhaustible supply of the best quality of road-building material.

Chapter V treats of the Upper Huronian series. This series is connected in the northern part of the area described with the Upper Marquette series of the adjoining Marquette district, and is considered to correspond stratigraphically to the Upper Marquette. Owing to lack of exposures and to the intricacy of folding, the series could not be subdivided. It covers a great area surrounding the Hemlock formation, and extends beyond the limits of the map. The exposures are scanty. It influences the topography only in a very general way, being for the most part heavily drift covered. Its thickness could not be estimated. The rocks of this series wrap around the subjacent Lower Huronian series. The line between them is undulatory. The indentations in the Lower Huronian represent minor cross synclines, and the protuberances represent minor cross anticlines. The most prominent fold of the series is known as the Crystal Falls syncline. The strike of the axis of this syncline is in general to the south of west, and pitches in the same direction. The syncline is not simple, but has minor rolls, as shown in various exposures. This folding has been productive of extensive reibungsbreccias. The folding occurred immediately preceding the deposit of the Keweenawan series in other parts of the Lake Superior region. The Upper Huronian is penetrated by intrusive rocks of acid, intermediate, and basic composition. The rocks constituting the series may be divided into those of sedimentary and those of igneous origin. The sedimentary rocks are graywackes, ferruginous graywackes, micaceous, carbonaceous, and ferruginous clay slates and their crystalline derivatives, and thinly laminated cherty siderite-slate, ferruginous chert, and iron ores. In two places rocks of conglomeratic nature occur. The extensive folding which the series has undergone, coupled with the intrusions of the igneous rocks, has produced crystalline schists from the muds and grits. These are extensively developed in the southern portion of the district in the vicinity of the Paint and Michigamme rivers. The igneous rocks which have penetrated the Upper Huronian subsequent to the folding which affected it are not described under the series. Interlaminated with the crystalline schists there are, however, certain rocks, now perfectly crystalline hornblende-gneisses, which are presumed to have resulted from the metamorphism of either basic intrusive sheets or interbedded flows.

The economic development of the district followed that of the adjoining Menominee district. The exploited ore deposits occur near Amasa, and in the vicinity of Crystal Falls. The ore is hematite and limonite. The grade is non-Bessemer. The ore is associated with white and reddish chert, and this formation lies between carbonaceous slates. The ore bodies in general pitch to the west at varying angles, which correspond to the pitch of the axes of the synclines in which they occur. These minor folds in turn correspond to the western pitch of the main Crystal Falls synclinorium. The ore bodies are concentrates in synclinal troughs, as described by Van Hise for other Huronian districts. The mining is now for the most part undergound, and is carried on in open stopes. The greatest shipment of ore from the area, including the Lower Huronian Mansfield mine, was 586,970 tons in 1892. The total shipment for 1898 reached 325,814 long tons.

Chapter VI treats of the intrusives. There is here included a varied assortment of rocks, exhibiting in common intrusive relations to the sedimentary and igneous rocks. The term "intrusive" is not to be interpreted as synonymous with the "dike rocks" of some authors. These rocks are never found to penetrate the Cambrian rocks, and have not been affected by the folding which metamorphosed the Upper Huronian sediments. They are presumed to be of Keweenawan age. The intrusives have in some cases been injected along the axes of the folds, these representing the lines of greatest shattering, and hence least resistance.

In Section I there are described a number of intrusive rocks which can not be connected genetically with one another. These comprise ordinary biotite-granites, with micropegmatitic varieties, muscovite-biotite-granite, metadolerite, metabasalt, and picrite-porphyry. Where the granites have intruded the Upper Huronian series they have contorted the strata, and include and metamorphose the rocks, producing muscovite-biotite-gneiss, and staurolitiferous and garnetiferous mica-schists. The metadolerites possess no special points of interest in themselves, but where they have intruded the Mansfield slates they have caused interesting exomorphism. The slates are converted into adinoles, spilosites, and desmosites. Chemical analyses indicate the chief change which has taken place in the production of these rocks from the clay slate to have been in the increase of silica and soda as the contact is approached. There seems thus to have been a direct transference of sodium and silicon from the igneous rock to the sedimentary. The metabasalt dikes are of little interest. The ultrabasic picrite-porphyries are extremely altered. This alteration has produced in one case chiefly tremolite and in another serpentine. One of these serpentine picrite-porphyries is polar-magnetic. The picrite-porphyries are presumed to have contained a vitreous base, and correspond to the modern Tertiary limburgite.

In Section II there is given a study of a series of rocks varying from those of intermediate acidity through those of basic composition to ultrabasic kinds. The exposures of these rocks are found in an area underlain by the Upper Huronian series, extending from Crystal Falls southeast to and a short distance beyond the Michigamme River. The prevailing rocks are, on the one hand, diorites of intermediate acidity, ranging to more acid rocks, tonalites, quartz-mica diorites, and granite. On the other hand, we have hornblende-gabbros, gabbros, norites, and, lastly, peridotites of varying mineralogical character. Only those kinds of rocks of which analyses have been obtained—mica-diorite, hornblende-gabbro, norite, and wehrlite—are discussed. The diorites are holocrystalline rocks of medium to coarse grain. In texture they show some variation from those which are hypidiomorphic granular to those in which the texture is imperfectly ophitic. As facies of the dioritic magma there are described diorite, mica-diorite, quartz-mica-diorite, tonalite, and plagioclase-bearing granite. A quartz-mica-diorite-porphyry occurs in narrow dikes cutting the mica-diorite. Analysis of the mica-diorite shows it to stand upon the border between the lime-soda feldspar rocks and the orthoclase rocks. The gabbros and norites are holocrystalline rocks of moderately fine to coarse grain. They show considerable variation in texture. The hypidiomorphic granular texture predominates, but some few show a good parallel texture. Others are noticeably porphyritic, a few have poikilitic textures, and less commonly there is an approach to the ophitic texture. Hornblende and labradorite is the most common mineral association, giving typical hornblende-gabbro. A monoclinic pyroxene at times becomes abundant, giving a transition to the normal gabbro. Bronzite at times is the prominent bisilicate constituent of these rocks, giving bronzite-norite. A bronzite-norite-porphyry also occurs. Locally the hornblende-gabbro has been crushed, and there is produced therefrom a schistose rock which represents a transition to a hornblende-gneiss. Of these rocks the hornblende-gabbro was first formed. It was intruded by normal gabbro, and both of these types were then cut by dikes of bronzite-norite and bronzite-norite-porphyry. The rocks included under the peridotites show considerable mineralogical variation. There is produced an amphibole-peridotite, which, when augite becomes predominant, grades to wehrlite. This in its turn becomes feldspathic, and indicates a transition to olivine-gabbro. The amphibole-peridotite also becomes feldspathic and quartzitic, indicating a transition toward diorite. When the order of crystallization of the minerals composing the granular rocks of the entire series described above is considered, it is seen to have been as follows: Bronzite is apparently the oldest. The olivine and monoclinic pyroxene come next and are of essentially the same age. Mica and hornblende follow, and are contemporaneous. Then comes plagioclase, orthoclase, and quartz. A consideration of the chemical analyses of the rocks above described shows them to belong to a series ranging from a diorite, on the one hand, to hornblende-gabbro and norite and to peridotite on the other. On the acid side of the series variations are shown microscopically, but of these rocks chemical analyses have not been obtained. It is not possible to state which of these rocks most nearly resembles in its composition the original magma of which the different

types represent the differentiation products. The hornblende-gabbro is that type which apparently first reached its present geological position. It was followed in the acid part of the series by the diorite, which in its turn was succeeded by the diorite-porphyry. Along the basic series hornblende-gabbro was succeeded by gabbro, followed by the bronzite-norite and the peridotite. In general the forces of differentiation have been toward increasing acidity and increasing basicity.

PART II.

CHAPTER I treats of geographical limits and physiography. The geographical limits of the area described are given and a brief statement made concerning the conditions under which the work was done. In the preliminary sketch of the geology the rocks represented are stated to range in age from Archean to early Paleozoic. In that part of the district north and west of the Michigamme River the Archean is exposed in several regularly outlined oval areas from 10 to 12 miles long and from 2 to 6 miles wide. The intervals between these ovals are occupied by highly tilted metamorphosed sedimentary and igneous rocks of Algonkian age. In the southern and eastern portions of the district the edges of the tilted rocks are covered by the gently dipping Cambrian sandstone. Nevertheless, field work shows that the distribution of the Archean in ovals, which is so characteristic for the areas north, also holds here. The chief surface feature is a rolling plain, which slopes gently to the southeast, and upon which is superimposed the glacial drift with its characteristic topographical features, multitudinous in variety and detail, but insignificant in relief. While the details of the topography are mainly glacial, the broader features have often clearly been determined by the presence of the more resistant Archean and Algonkian rocks. The drainage is to the southeast, mainly into Lake Michigan, through the Michigamme and the Sturgeon rivers. Details of the drainage have been determined by the distribution of the rocks. It is interesting to note that the Michigamme flows along the eastern edge of its drainage basin, having no eastern tributaries.

CHAPTER II treats of magnetic observations in geological mapping. Certain of the rocks occurring in the Crystal Falls district contain magnetite in such quantity that they have a marked influence on the magnetic needle. Advantage is taken of this fact in the mapping of the rocks where exposures are wanting. The instruments and methods of work used in making magnetic observations are described. Facts of observation are mentioned, and general principles are laid down. Application of these principles to special cases is then considered, and finally a description of the method used in the interpretation of complex structures follows.

CHAPTER III. In Section I the position, extent, and previous work done in the Felch Mountain range is described. An abstract of the literature covering the area is given.

Section II contains a general sketch of the geology of this range. The rocks range from Archean to early Paleozoic. These last are not considered for the present. The Archean is distributed in areas which represent the cores of large arches formed over the whole region by mountain building energy, and subsequently truncated by deep Cambrian denudation. The rocks, chiefly of sedimentary origin intermediate between the Archean and Paleozoic, to which the name Algonkian is applied, occupy a narrow strip ranging from a mile and a half to less than a mile in width, and extending east and west for a distance of over 13 miles. This strip constitutes the Felch Mountain range. It is bordered on the north and south by the Archean. The lowest part of the Algonkian occupies parallel zones next to the Archean both on the north and on the south, and is succeeded toward the interior of the strip by the younger members. The general structure therefore is synclinal, but is not simple. The strip contains two or more synclines separated by anticlines. They have likewise been affected by cross folds, which give a different pitch to the axes of the east and west folds. The structure is also complicated by faulting. The Algonkian is divided into two series separated by an unconformity. In the first occur, from the base upward, the Sturgeon quartzite, the Randville dolomite, the Mansfield schist, and the Groveland iron formations. Above these follows a younger series which is undivided.

Section III treats of the Archean. This limits the Algonkian rocks on the north and south, and is very well exposed. The topography is very rough. Usually, but not always, a topographical

depression, occupied by a swamp or by a stream, exists along the contact between the Archean and the Algonkian. Petrographically the Archean consists of (1) granites or granitic gneisses, (2) gneisses, (3) mica-schists, (4) hornblende-gneisses, or amphibolites. The granites possess the usual characters of such rocks. The gneissoid members of this division are merely crushed granites, and are connected with the massive rocks by indistinguishable gradations. The gneisses are banded laminated rocks, the minerals of which have crystallized in parallel elongated forms. Subsequent to crystallization they have been acted on by great stresses. The mica-schists are even, medium-grained rocks, with generally well-developed schistosity. The original character of these schists is wholly indeterminable. Their relationship with the granites and gneisses is perhaps a reason for regarding them as derived from originally massive granites by dynamic metamorphism. The hornblende-gneisses, or amphibolites, are black or dark-green rocks, which are universally foliated. They occur in narrow bands in the granites and gneisses. Their boundaries are sharp and frequently cut the foliation of the amphibolites and of the gneisses. The field relation as well as the composition of the amphibolites leads to the conclusion that they are old dikes of basic rocks which have been metamorphosed and recrystallized.

Section IV treats of the Sturgeon quartzite. The Sturgeon formation is the most widespread member of the Algonkian series in the Felch Mountain range. It occurs in two parallel zones of varying width, immediately adjoining the Archean to the north and to the south, except when displaced from this position by faults. It is fairly well exposed. It frequently forms distinct lineal ridges, which, with but few exceptions, seldom rise to the mean altitude of the adjoining Archean. Owing to the completeness of recrystallization, the original sedimentary features have almost been obliterated, so that it is difficult to find places suitable for dip observations. Sufficient dips have been found to show that subordinate folds occur within the quartzite. The average thickness is probably not less than 450 feet, and may be more. Petrographically the formation includes massive quartzites and mashed quartzites or micaceous quartz-schists, in some of which the relations of the quartz present unusual features.

Section V. The Randville dolomite, consisting of crystalline dolomitic rocks, overlies the Sturgeon quartzite. The Randville dolomite covers a larger share of the surface in the Felch Mountain range than any other member of the Algonkian. Natural exposures are fairly numerous and very evenly distributed. Moreover, test pits and diamond-drill borings have shown the presence of the formation in the covered areas. Relatively the dolomite is a weak rock, and occupies relatively low ground. An average thickness of 700 feet is estimated for the Randville dolomite within the Felch Mountain range. Petrographically the formation consists of a rather coarse-grained, thoroughly crystalline dolomite, with more or less abundant crystals of tremolite and a number of other minerals of minor importance.

Section VI. The Mansfield schist is only exposed in certain test pits. Its presence has also been determined by diamond-drill borings. The thickness is so small—not more than 200 feet—that, though it weathers readily, it produces no noticeable effects on the general topography. Petrographically it consists of fine-grained mica-muscovite or mica-biotite-schists, probably derived from the metamorphism of a clast'c. It shows nothing of especial interest.

Section VII. The Groveland formation is magnetic and has been traçed by means of compass and dip needle. Excellent natural as well as numerous artificial exposures render the data concerning the distribution of the formation very satisfactory. The most prominent hills in the Algonkian belt owe their relief to the fact that they are underlain by the Groveland formation. Petrographically we may recognize two main kinds of rock. The usual kind consists of quartz and the anhydrous oxides of iron, while the other and much rarer consists essentially of an iron amphibole with quartz and the iron oxides as associates. Both of these kinds are clearly of detrital origin. The conclusion is reached, based on certain microscopical structures, that iron and silica were originally present largely in the form of glauconite.

Section VIII. Mica-schist and ferruginous quartzites of the Upper Huronian series occur in the eastern part of the Felch Mountain range. The rocks constituting the series are soft iron-

stained mica-schists, with thin, interbanded beds of ferruginous and micaceous quartzite. Neither kind shows traces of clastic origin. From their structures and general relations they are believed to have been derived from sedimentary rocks by metamorphism.

Section IX. The Algonkian rocks are cut by intrusives, among which both acid and basic rocks are represented. The acid rocks are granites occurring in narrow dikes. No dikes of granite are known to cut the Randville or Mansfield formations.

CHAPTER IV treats of the Michigamme Mountain and Fence River areas. These areas occur in the central part of the district. In the Fence River area the structure is very simple. In the Michigamme Mountain area the structure is complex.

Section I treats of the Archean. The prevalent rock is granite, cut by acid and basic dikes.

Section II treats of the Sturgeon formation. This is scarcely known as a distinct Algonkian member in this area apart from the Randville formation. In one section purely clastic sediments were observed, for which it is convenient to retain the name. These exposures consist of slates and graywackes, with some layers of a coarser texture.

Section III treats of the Randville dolomite. In the Fence River area the dolomite lies on the east side of the Archean and occupies a belt about one-half mile in width, and extending from the mouth of the Fence River about 10 miles to the north and west, where it leaves the portion of the district studied. In the Michigamme Mountain area the dolomite tops the low arch in a broad crumpled sheet. The formation in the Fence River area occurs in an eastward-dipping monocline with a number of minor plications. An average thickness of about 1,500 feet is estimated for the formation in this area. In the scattered outcrops of the Michigamme Mountain area the dolomite strikes and dips toward all points of the compass, caused by the gentle arching from the general northwest-southeast axis, combined with sharp local folds which run nearly east and west. Petrographically the formation ranges from coarse saccharoidal marbles, sometimes very pure but usually filled with secondary silicates, to fine-grained, little-altered limestones, which are occasionally so impure as to be calcareous or dolomitic sandstones and shales. The prevalent colors are white, but various shades of pink, light and deep blue, and pale green occur. Some of the varieties are oolitic. This structure does not seem to have been noted previous to this in limestones of pre-Cambrian age.

Section IV treats of the Mansfield formation. The typical locality of this formation is in the vicinity of the Mansfield mine, which lies to the west of the district studied. Where it occurs in the Michigamme Mountain area, the formation consists of phyllites or mica-slates of various colors. The structure of this area is so complex and the outcrops so few as to forbid any but an approximate outlining of the general boundaries of the formation. The geological position of the formation is free from doubt. It overlies and passes downward into the Randville dolomite. The formation does not seem to influence the topography. Like the preceding one, it has been extensively folded. The average thickness is probably not less than 400 feet. The mica-slates or phyllites possess no especial petrographical interest.

Section V treats of the Hemlock formation. The Mansfield formation of the Michigamme Mountain area changes along the strike into rocks of a different character, to which the above name is given. In the Fence River area it occupies a belt between 2,000 and 3,000 feet in width, between the Randville dolomite on the west and the Groveland formation on the east. The best exposures occur on the sections made by the Fence River. No folds have been observed within this formation. The thickness probably varies from 0 to 2,300 feet as a maximum. The rocks of the formation are chiefly chloritic and ophitic schists, with which are associated schists bearing biotite, ilmenite, and ottrelite; greenstone, conglomerates or agglomerates, and amygdaloids. The general characters of the schists are (1) a groundmass composed of chlorite, quartz, magnetite, epidote, and in some cases plagioclase microlites, and (2) the presence in this groundmass of much larger porphyritic individuals of several secondary minerals. As evidence of the origin of these schists, first, there is the absence of rocks possessing any sedimentary characters; next, lavas and also greenstone-conglomerates or agglomerates are undoubtedly present in the series; furthermore, the minerals which compose the schist are those which would result from the alteration in connection with dynamic metamorphism of

igneous rocks of basic or intermediate chemical composition; and finally, the grain and character of the groundmass, and in some slides the presence of plagioclase microlites disposed in oval lines point directly to an igneous origin and to consolidation at the surface. The conclusion is reached that the Hemlock formation of the Fence River area is composed of a series of old lava flows varying in composition from acid to basic.

Section VI treats of the Groveland formation. This is of wide extent throughout this part of the Crystal Falls district, but its outcrops are limited to three localities. Its distribution has been determined by means of its magnetic properties. It is not topographically prominent, except in the Michigamme Mountain area, where it forms part of Michigamme Mountain. In the Fence River area it is probably not folded. It there dips to the east. At Michigamme Mountain it is found in several well-marked folds. The thickness of the formation is estimated to be approximately 500 feet. The rocks are interbanded ferruginous quartzite and actinolite and grünerite schists, which still contain evidence of detrital origin.

Chapter V treats of the Northeastern area and the relations between the Lower Marquette and the Lower Menominee. The territory included in the Northeastern area extends from the northernmost outcrops of the Fence River area to the northern end of the Republic trough, a distance of about 11 miles. Outcrops are scarce throughout this area, and the main conclusions are drawn from the magnetic work. Through the structural and lithological results of the magnetic work the gap between the Marquette and the Crystal Falls district is bridged, and it is shown with a high degree of probability that the Negaunee iron formation of the Marquette range is identical with the Groveland iron formation of the Felch Mountain range.

Chapter VI treats of the Sturgeon River tongue. In the southeastern part of the Crystal Falls district and just north of the Felch Mountain range a tongue of fragmental rocks extending eastward has been studied. The extreme length is 12 or 13 miles. Its width at its eastern end is 1½ miles; to the west it widens rapidly. It is bounded both to the north and to the south by Archean granites and schists; to the east it is overlain by Paleozoic sandstones and limestones; and at its west end it is covered by glacial deposits. Within the tongue two small granite islands occur. The Archean or Basement Complex rocks comprise gneissoid granites, hornblende-schists, and biotite-schists, which are cut by dikes of greenstone and granite, and veins of quartz. The sedimentary rocks comprise conglomerates, arkoses, quartzites, sericite-schists, clay slates, rocks that are probably tufaceous, dolomitic limestones, and calcareous sandstones and slates. They may be divided into a conglomerate series and a dolomite series. From the distribution of the exposures of the two series it is concluded that the conglomerate series is the older, and that conformably above it follows the dolomite series. The two form a westward-pitching syncline. The conglomerate series and the dolomite series are correlated respectively with the Sturgeon quartzite and the Randville dolomite of the adjoining Felch Mountain range.

THE CRYSTAL FALLS IRON-BEARING DISTRICT OF MICHIGAN

Part I.—THE WESTERN PART OF THE DISTRICT

By J. MORGAN CLEMENTS

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HURONIAN

- Ah 1 *The Original Huronian.*
- Ah 2 *The Marquette Iron-Bearing Series,*
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ARCHEAN	ALGONKIAN		POST-ALGONKIAN
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HURONIAN

- Ah 1 The Original Huronian
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GEOLOGIC MAP OF PART OF THE LAKE SUPERIOR REGION

Compiled from Official maps of U.S. Minnesota, and Canadian Surveys

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THE CRYSTAL FALLS IRON-BEARING DISTRICT OF MICHIGAN.

PART I. THE WESTERN PART OF THE DISTRICT.

By J. Morgan Clements.

CHAPTER I.

INTRODUCTION.

The present report is an account of a portion of the Crystal Falls district of Michigan, so called from the most important town, Crystal Falls, the county seat of Iron County. The iron-bearing district along the Paint River, near the site of the town of Crystal Falls, was first called in literature the Paint River district by Brooks.[1] As soon as the town was begun, about 1880, the name of the town was applied to the district.[2] It is situated on the Upper Peninsula of Michigan, adjoining the northeastern border of Wisconsin, and serves as a link connecting the two well-known iron-ore-producing districts of Michigan, the Marquette, and the Menominee. The Crystal Falls district is of itself of considerable economic importance, as will be seen, though not deserving to be ranked with either of the two above-mentioned iron districts. Since the geological relations of the rocks

[1] The iron-bearing rocks (economic), by T. B. Brooks: Geol. Survey of Michigan, Vol. I, Part I, 1873, p. 182.

[2] Rept. Com. Min. Statistics Mich. for 1881, p. 222.

of the Marquette district have now been ascertained,[1] it is hoped, by means of the determination of the succession in the intermediate Crystal Falls district, that the Menominee rocks may be closely correlated with those of the Marquette district.

The accurate delimitation of the iron-bearing or coal-bearing formations, or any other formations containing valuable mineral products, is of inestimable value to miners and investors. In the iron districts of Michigan alone innumerable test pits have been sunk in areas of solid granite, and at great distances outside of the possible iron formations, thus wasting large sums of money. Although the investigations carried on in the Crystal Falls district, the results of which are here recorded, do not enable us to point out definitely the places where the prospector will find iron deposits, they have enabled us to delimit in a broad way the various formations, and warrant the statement that iron deposits may occur in certain areas and that the prospector will assuredly not find iron deposits in certain others.

The opportunity of studying the Crystal Falls district was given me through Prof. C. R. Van Hise. In the prosecution of the field studies and in the preparation of the report I have availed myself of his advice and suggestions, which have been generously offered and which have been found of greatest value. To him I am most deeply indebted.

The report is based not only on my own field work, but also on the field work done by a number of other geologists, whose notebooks have been placed at my disposal. The names of these geologists may be found on page 22. Among them, the notes of Mr. W. N. Merriam and Dr. W. S. Bayley have been found especially valuable. Mr. Merriam, assisted by Dr. Bayley, spent a season in doing very detailed work on the area shown on the sketch map at the bottom of Pl. III, between Crystal Falls and Mansfield, and from this point northwest to some distance beyond Amasa. The magnetic lines represented in this part were traced by Mr. Merriam, and the geology in general is the same that he outlined on his final field map

I wish to thank Mr. C. K. Leith, who has been of the greatest clerical assistance, and Mr. E. C. Bebb, by whom the maps were drawn; also Mr.

[1] The Marquette iron-bearing district of Michigan (preliminary), by C. R. Van Hise and W. S. Bayley; with a chapter on the Republic Trough, by H. L. Smyth: Fifteenth Ann. Rept. U. S. Geol. Survey, 1895, pp. 477–650. Ibid. (final), Mon. U. S. Geol. Survey, Vol. XXVIII, 1897.

J. L. Ridgway, by whom the colored plates of natural size specimens were prepared.

PREVIOUS WORK IN THE DISTRICT.

On account of its comparatively slight economic importance, and also on account of its isolation, very little work of which the results have been published was done in this district prior to that on which this monograph is based. As a rule, the earlier observers began the season's work either in the Marquette or in the Menominee range, and working westward the Crystal Falls district was reached only as the season neared its close, or as the appropriation was nearly exhausted. The published work upon this district is given below in chronological order.

1850.

Burt, Wm. A. Report of linear surveys with reference to mines and minerals, in the Northern Peninsula of Michigan in the years 1845 and 1846. Dated March 20, 1847. Thirty-first Congress, first session, 1850; Senate documents, Vol. III, No. 1, pp. 842–882, with map.

During the year 1846 a linear survey was made of that part of the Upper Peninsula of Michigan described as being bounded on the north by the fifth correction line, on the south by the fourth correction line and the Brule River, on the east by ranges 23 and 26 W., and on the west by range 37 W. This includes in its limits the district under discussion. In the course of the survey, geological observations were made by William A. Burt, the deputy surveyor in charge of the work. The report and accompanying geological map embodying the results of these observations are concealed among the Senate documents of the Thirty-first Congress. The following quotations from this report give all the observations on the part of the territory surveyed in which we are at present interested:

Topography.—West of range 31 west, and north of the Brule River to the fifth correction line, is a tract of about 43 townships in which the rock is mostly greenstone and hornblende slates. This part of the surveyed district is less broken than that above described, and a large proportion of it may be denominated rolling lands. There are, however, many ridges and conical hills of various heights upon this part of the survey, and also deep valleys of streams, many of which have ledges upon their sides. These general characteristics are often changed for cedar, spruce, or tamarack swamps, which are most numerous in townships 46, 47, and 48 N. [This includes the part of the district supposed to be the continuation of the northern Wisconsin peneplain (p. 31).]

Granite (and syenite).—These rocks occupy an area of about 22 townships on the northeast part of the survey, between the fifth correction line and the south boundary of township 45 N., and east of range 32 W., in a series of irregular uplifts, frequently forming high cliffs and sloping ledges on the most elevated portion of this district. [This covers a part of the Archean granite oval of the Crystal Falls district, as well as the large Archean areas northeast of it.]

Argillaceous slates.—The argillaceous slates alluded to in townships 42 and 43 N. are generally overlaid by deep drift; their boundaries, therefore, could not be satisfactorily defined. West of the Peshakumme River these slates appeared to have undergone considerable change by igneous action, and were often associated with an oxide of iron; but east of the Peshakumme no change by igneous action in the slates was observed, and on this part they have generally a reddish color. . . . .

They dip variously at a high angle, and are supposed to conform to the greenstone on the north and west, and to overlie or pass into the mica-slates on the south; and in their middle portion they dip about 90°, with strike nearly east and west. [These slates correspond to our least metamorphosed phases of the Upper Huronian.]

Greenstone and hornblende slate.—These rocks occupy a larger area in the district surveyed than any other class of rocks. They extend from the granitic and other rocks east of them westward beyond the survey. [See their outline on map, fig. 1.]

The greenstone and hornblende slates form a less broken surface than the granitic range; and next to it is the most elevated range in this district, having an estimated altitude, in many places, of from 1,000 to 1,100 feet above Lake Superior.

These rocks are frequently seen in the beds and banks of streams and in ridges and conical hills of various heights, often forming precipitous ledges upon their sides. . . . .

The greenstone of this region is generally more or less granular and syenitic, with a dark-green color when moist; its composition is hornblende, feldspar, and quartz—the former mineral greatly predominating. In some places the feldspar and quartz are nearly or quite wanting, leaving a granulated hornblende rock. Another variety of this rock was frequently seen which was composed of the same ingredients but very fine grained and compact and having frequently a laminated or slaty structure, the cleavages of which generally dip from the granitic rocks at a very high angle. . . . .

Some of these hornblende slates have in their seams and cleavages a silky luster, from the presence of mica or talc in very fine grains. . . . .

All of these rocks are traversed by many quartz veins, from a line to 4 feet or more in width, and with still larger veins and dikes of more recent trap rock. This range is supposed to have become blended with the trap range of Keweenaw point as it passes under the red sandstone lying between them, and probably farther west the two are united in one range. [These are the altered and more or less schistose basalts and accompanying fragmentals which are comprised in the Hemlock formation.]

Mica-slates.—These slates stretch along the southerly side of the argillaceous slates on the south part of the survey. They extend from the Brule River on a course east-northeast for about 22 miles, in townships 41 and 42 N., ranges 29, 31, and 32 W., and have an average breadth of about 4 miles. . . . .

The mica-slates are supposed to dip northerly under the argillaceous slates at a high angle, varying at the surface from 45° to 80°. . . . .

This rock is composed of mica, quartz, and feldspar. Its laminæ are undulating or waved, but its cleavages, on a large scale, are even and regular. . . . .

These mica-slates are best developed on the south boundary of township 42 N., ranges 31 and 32 W., in the beds and banks of the Peshakumme and Mesqua-cum-a-

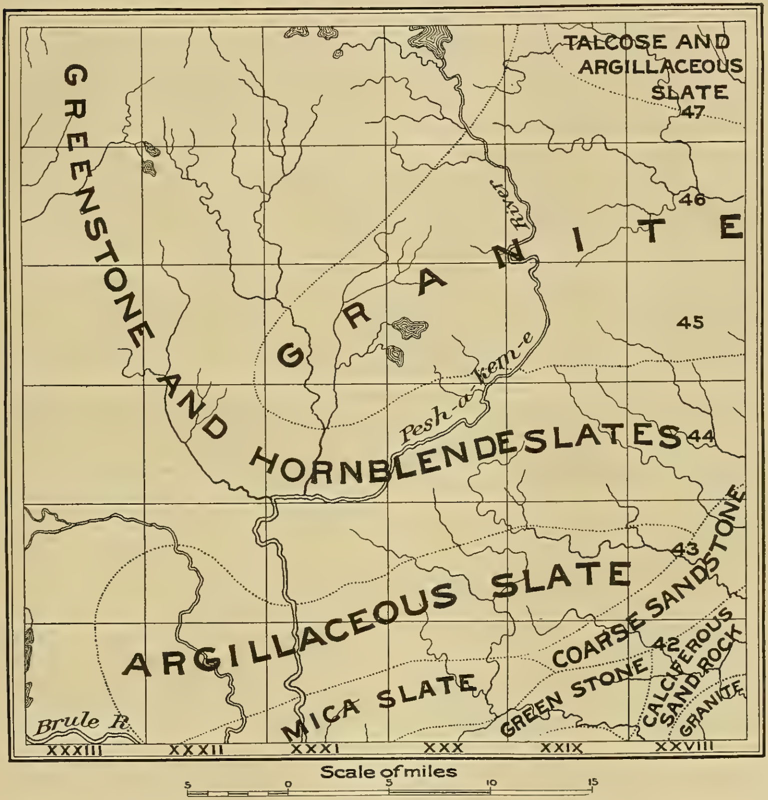


Fig. 1.—Reproduction of a portion of the geological map of the Upper Peninsula of Michigan by Wm. A. Burt, 1846.

cum-sepe, and at the falls near the junction of the latter stream with the Brula River. [These, according to our observations, are the most altered phases of the Upper Huronian.]

That part of the geological map accompanying the above report which corresponds to the Crystal Falls district is reproduced in fig. 1.

1851.

FOSTER, J. W., and WHITNEY, J. D. Report on the geology of the Lake Superior land district. Part II. The iron region, together with the general geology. Thirty-second Congress, special session, 1851; Senate documents, Vol. III, No. 4, pp. 406, with maps and section.

In 1851 there was published a report by Foster and Whitney on the iron regions of the Lake Superior land district, together with the general geology. This gives the first connected account of the results obtained by the various surveyors who had been engaged on the Government survey of the Upper Peninsula of Michigan. Accompanying this report there are two colored maps and a section. The subdivisions of the rocks as made by Burt in the Crystal Falls district are not retained in this report by Foster and Whitney. The map is generalized, and the hornblende-slates, etc., of Burt are included under the general term "crystalline schists," and are placed by the authors in the Azoic system. There are represented here and there throughout this Azoic area a trappean knob and bed of marble.

The granite area shown on Burt's map is very much reduced in size, and no longer connected with the large granite areas to the east. The granite on the lower reaches of the Michigamme, in T. 42 N., R. 31 W., is here indicated for the first time. In these respects only does this portion of the map show a decided advance in knowledge of the distribution of the rocks. A copy of the map, showing the distribution of the rocks by symbols instead of colors, is reproduced as fig. 2.

1873.

BROOKS, T. B. The iron-bearing rocks (economic). Geol. Survey of Michigan, Vol. I, Part I, 1873, pp. 319. With Atlas Plate IV and general map, by Rominger, Brooks, and Pumpelly.

The next mention of the district that I have been able to find was made in 1873 by Maj. T. B. Brooks, in his report on the iron-bearing rocks of Michigan.

However, this report seems to show a decided decrease in knowledge from that possessed by Burt concerning the geology of this district. It is true that indications of iron had been seen, but the observations made were so meager that nothing could be done toward determining the relations of the rocks or unraveling the structure of the area.

Upon the map accompanying the report (Geol. Survey of Michigan,

1873), a portion of which is reproduced in fig. 3, Brooks has failed to outline the granitic areas known to the previous explorers. Except in a

FIG. 2.—Enlarged reproduction of a portion of a map of the Lake Superior land district, by Foster and Whitney. G=granite; T=trappean rocks; ♂=iron; [marble symbol]=beds of marble.

Metamorphic formation.
Azoic system.
Quartz. Crystalline schists.

Igneous formation.
(Associated with the Azoic.)
Trappean rocks. Granite.

few places, which have been left uncolored, the district is covered with the color representing the Huronian.

Brooks refers the ore-bearing rocks to the Huronian in the following words:

> Too little is known about the remote Paint River district, in townships 42 and 43, ranges 32 and 33, to enable me to give anything of interest regarding its geological

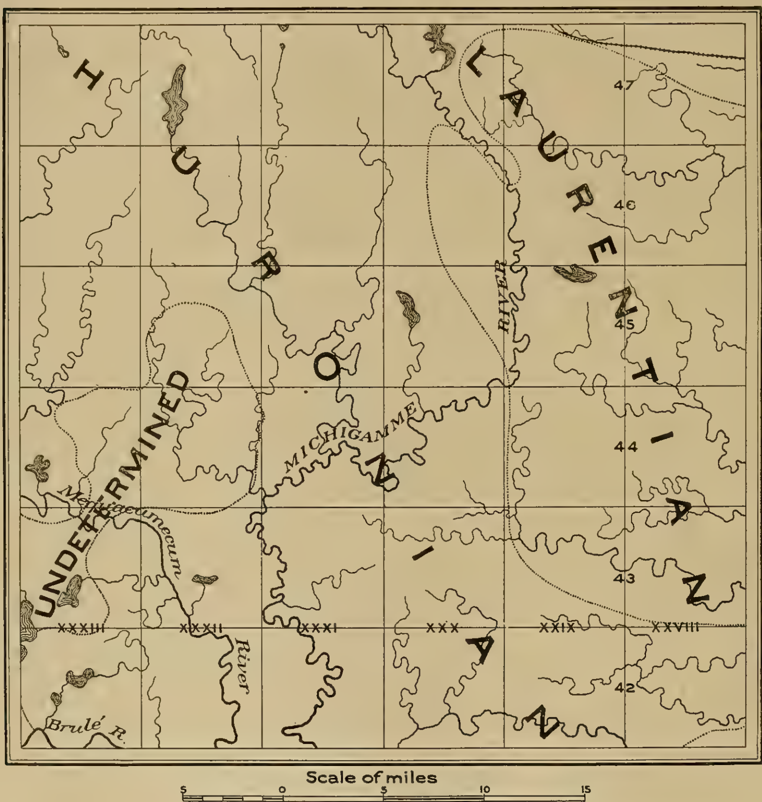
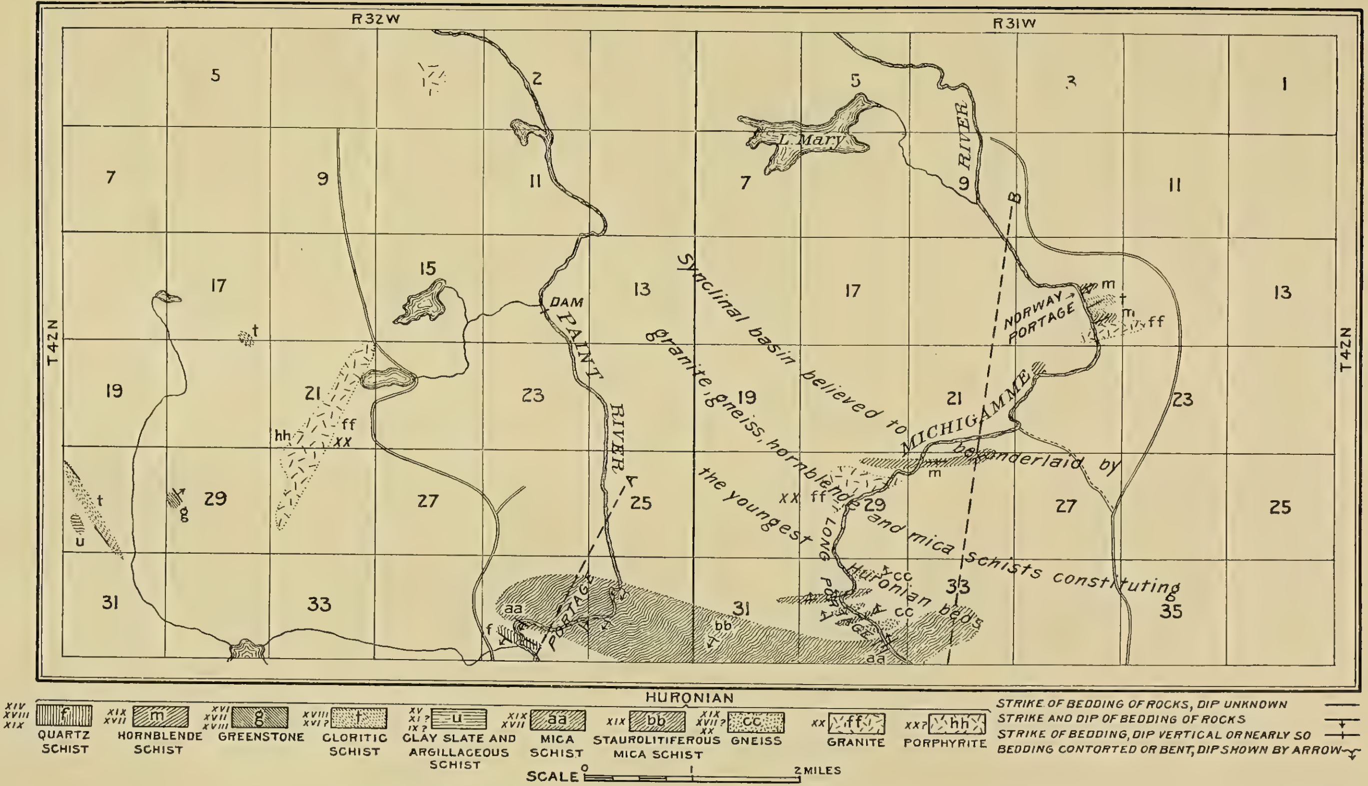


FIG. 3.—Enlarged reproduction of portion of a geological map of the Upper Peninsula of Michigan, by C. Rominger, T. B. Brooks, and R. Pumpelly, 1873.

> structure. The Huronian rocks are extensively developed there, and contain deposits of hard hematite ore. I had the opportunity to examine only two localities at the Paint River Falls, sec. 20, T. 43, R. 32, and sec. 13, T. 42, R. 33, (p. 182).



PORTION OF A GEOLOGICAL MAP OF THE MENOMINEE IRON REGIONS, BY T. B. BROOKS AND C. E. WRIGHT.

Reproduction in line drawing of original colored map

He also gives his analysis (No. 68, p. 302 of Brooks's report) of an ore sample from the district, and calls attention to its abnormally high water content, freedom from silica, and richness in iron as compared to those of the more eastern mines in the Menominee region.

1880.

BROOKS, T. B. Geology of the Menominee region. Geol. Survey of Wisconsin, Vol. III, Part V, 1880, pp. 430-655. Atlas folio. Pls. XXVIII and XXIX, and Pl. XXX, by C. E. Wright.

In an article on the geology of the Menominee region, which was written for the geological survey of Wisconsin, the same author briefly touched on that part of the adjoining Michigan territory which is included in the district under consideration. His observations were thus confined to a few exposures in a limited portion of the area. He attempts to correlate certain beds by means of their lithological character with those with which he was familiar in the Marquette district and refers them uniformly to the higher members of the Huronian.

They are also so referred on the map which accompanies the report, though this is dated a year earlier than the date of publication of the report. That portion of the map covering a small part of the Crystal Falls region is reproduced on Pl. IV. The present survey enables us to add very little to this, and these additions are chiefly of a petrological character.

1881.

ROMINGER, CARL. Geology of the Menominee iron region. Geol. Survey of Michigan, Vol. IV, 1881.

In 1880 Dr. Carl Rominger, at that time State geologist of Michigan, spent a season in the Menominee district, and in his report gives detailed descriptions of a few occurrences in the Crystal Falls district, to which I shall refer later on. He considers the rocks in general to belong to the Huronian, and distributes the beds among his diorite group, iron-ore group, and arenaceous-slate group, as given and defined in the previous report on the Marquette district No attempt at more definite correlation was made.

1890.

VAN HISE, C. R. An attempt to harmonize some apparently conflicting views of Lake Superior stratigraphy. Am. Jour. of Sci., 3d series, vol. 41, 1891, p. 133.

On December 30, 1890, Prof. C. R. Van Hise read a paper on Lake Superior stratigraphy before the Wisconsin Academy of Sciences, Arts, and

Letters, the same article being published the following year in the American Journal. The iron-bearing series of this district was in this article referred to the Upper Marquette (Upper Huronian).

1893.

Wright, C. E. Report of State geologist from May 1, 1885, to June 1, 1888, in Rept. of the State Board of Geol. Survey of Michigan, 1893, pp. 33–44.

State geologist, Charles E. Wright, in a report for the seasons from 1885 to 1888, inclusive, merely mentions the general strike of the rocks of the district, and makes no attempt to determine their age nor to unravel the structure.

Wadsworth, M. E. Sketch of the geology of the iron, gold, and copper districts of Michigan. In Rept. of State Board of Geol. Survey for years 1891–92, 1893, pp. 75–186.

Dr. M. E. Wadsworth, who on Mr. Wright's death succeeded him as State geologist of Michigan, mentions the occurrence of carbonaceous slates, of granite and melaphyre, and of conglomerate near Crystal Falls, but does not enter into a discussion of the relations of any of these rocks. Dr. Wadsworth agrees with the correlation of Professor Van Hise, and places the Crystal Falls ore deposits in the Upper Marquette series (Wadsworth's Holyoke formation) (pp. 117, 132), but the evidence for so doing is not given in the report. He also is the first to recognize the volcanic nature of the rocks in the vicinity of Crystal Falls (p. 134).

1895.

Rominger, C. Geol. rept. on the Upper Peninsula of Michigan. Geol. Survey of Michigan, Vol. V, Part. I, 1895, pp. 1–164.

In his report of work done on the Upper Peninsula of Michigan from 1881 to 1884, published in 1895, he follows the same plan, referring the various rocks exposed by mining operations to his different groups.[1]

Clements, J. Morgan. The volcanics of the Michigamme district of Michigan. Jour. of Geol., Vol. III, 1895, pp. 801–822.[2]

In a preliminary article on this district, by the writer, published in 1895, the volcanic character of the rocks which cover a large area of the Crystal Falls district was emphasized, and in a sketch map in the same

[1] Geol. Survey of Michigan, Vol. IV, 1881, p. 8.

[2] After the publication of this article, the name Michigamme having been applied to a formation, it was deemed advisable, in order to avoid confusion, to change the name of the district to the Crystal Falls district.

article was given an outline of the distribution of the various rocks for a portion of the district, with their stratigraphical succession (p. 803), the discussion of the structure and correlation being left for the present report.

The above-mentioned sketch map, with the maps by Burt, Foster and Whitney, Brooks, Brooks and Wright, the section by Foster and Whitney, and the section by Brooks, along the Paint and Michigamme rivers, are the only maps or sections which, so far as can be learned, have been published of that part of the Crystal Falls district under discussion.

MISCELLANEOUS REFERENCES.

JULIEN, ALEXIS A. Appendix A. Lithology. Geol. of Michigan, Vol. II, 1873, pp. 1–185.

WICHMANN, ARTHUR. Microscopical observations on the iron-bearing rocks from the region south of Lake Superior. Brooks's Geol. of the Menominee Iron Region, 1880, Chap. V, pp. 600–655.

WRIGHT, CHARLES E. Geology of Menominee Iron Region. Geol. of Wisconsin, Vol. III, Part 8, 1880, pp. 665–741.

LANE, A. O. In sketch of the geology of the iron, gold, and copper deposits of Michigan. Rept. of State Board of Geol. Survey for 1891–92, 1893, p. 182.

PATTON, H. S. Microscopic study of some Michigan rocks. Rept. of State Board Geol. Survey for 1891–92, 1893, p. 186.

During the progress of the Michigan and Wisconsin State surveys specimens from outcrops were collected, and descriptions of these disconnected specimens are found in the State reports.

References to the pages on which the individual descriptions may be found will be given under the petrographical discussion of similar rocks here described.

UNPUBLISHED WORK.

In 1891 a survey was organized by a private corporation, and put in charge of Prof. C. R. Van Hise. He consented to take charge of this work on the conditions that all maps and notes should be available for this report and that no other compensation was to be made by the company. The object of this survey, known as the Lake Superior survey, was to study that part of Michigan of which Crystal Falls is the center, in order to determine the feasibility and advisability of opening up the mines of that district. This survey was vigorously prosecuted, and an excellent topographic map made of an area 32 miles north and south and 42 miles east and west, covering a large part of four 15-minute atlas sheets of the United States Geological

Survey. At the same time, in connection with the topographic work, a reconnaissance geological survey was made.

The following is a list of those who took geological notes for this survey: Andrews Allen, A. H. Brooks, W. S. Bayley, J. P. Channing, E. T. Eriksen, J. R. Finlay, F. J. Harriman, F. T. Kelly, E. B. Matthews, E. R. Maurer, J. A. McKim, F. W. McNair, W. N. Merriam, and H. F. Phillips.

The following season was devoted to a detail study of the iron-bearing belts which had been outlined by the reconnaissance. This detail work in the western part of the district was prosecuted by parties in charge of W. N. Merriam, and in the eastern part of the district by parties in charge of H. L. Smyth. When they ceased work, the two areas mapped were separated in the north by about 12 miles, and a narrow belt separated the mapped areas to the south. During the season of 1894, under the direction of Professor Van Hise and assisted by G. E. Culver, and during part of the season by S. Weidman, I was engaged in completing this unfinished work for the United States Geological Survey, preparatory to connecting this district with the Menominee iron-bearing district to the southeast. This work was carried on in 1895 by Dr. W. S. Bayley, S. Weidman, and myself, and the mapping of the district extended as far as the Menominee district.

Mr. H. L. Smyth has written Part II of the present report, covering the portion of the district which was worked by his party. My description of the part of the district worked by me is based largely on my own observations. Many of the facts of field occurrence, however, mentioned in the following paper were observed and recorded by the several men mentioned above, and were subsequently verified by my own observations in portions of the area surveyed by myself, and by visits to localities in other portions.

The topography of the greater portion of the district was taken by the members of the Lake Superior Survey. The remainder we owe to the topographical division of the United States Geological Survey. The areas covered by the respective organizations are shown on the sketch map below the topographical map (Pl. II).

MODE OF WORK.

As explanatory of the locations given in the paper, it is perhaps not out of place to give a brief description of the plan of work followed by the Lake Superior Division of the United States Geological Survey in this as

well as in the other Lake Superior iron-bearing districts which have been previously surveyed.

The Upper Peninsula of Michigan affords an excellent example of the excellence which can be obtained in the rectangular land survey, when properly carried out by the Government. The section corner posts originally established are in many cases still to be seen, and of course the bearing trees are even more common. Since the original survey the timber value has increased so much that in certain forested areas the section lines have been resurveyed. Not uncommonly trails follow the section lines for long distances. Moreover, the roads are frequently laid out along the section lines, thus giving permanent land boundaries. The section corners consequently offer the most reliable points from which to make locations.

Traverses are made across each section, either from east to west or from north to south, and at varying intervals, according to the discretion of the geologist and the exigencies of the case. Each geologist is accompanied by a compassman, whose duty it is to determine the course of the traverses by means of a dial compass, and the distance traveled by pacing at the rate of 2,000 steps to the mile. Corrections are made at the corner and quarter posts. The compassmen employed are Michigan woodsmen, land lookers or cruisers as they are frequently called, and it is remarkable with what accuracy they will pace mile after mile through swamp and over rough hills, windfalls, etc.

The geologist explores the territory on both sides of the line followed by the compassman. Ledges are located by the geologist pacing to the compassman as he comes opposite him in a due east-west or north-south direction. With two coordinates thus determined, the ledges are located with reference to the starting point. For uniformity and to facilitate reference and cataloguing, it is customary to give the location with reference to the southeast corner of the section. Thus, 1,000 N., 1,000 W., SE. cor. sec. 5, T. 42 N., R. 33 W., gives the location of the outcrop at the center of the section, and affords a means of finding that ledge which could not be so accurately and concisely stated by the use of any ordinary landmarks. Moreover, easily recognized landmarks, such as houses, quarries, etc., are few, and exceedingly great changes may occur very rapidly, such, for instance, as those caused by widespread forest fires, so that such a method of location is practically valueless.

MAGNETIC OBSERVATIONS.

It has long been known that many rocks are possessed of decidedly magnetic properties, due to the presence in them of varying quantities of magnetic iron ore. By the mining engineers and prospectors this property has been turned to a practical use in aiding in the location of iron mines where the ore is of a magnetic kind. It is only in the past three decades that this property has been used to any extent by geologists as an aid in the interpretation of the structure of a region. So far as I can learn, the best published account of its use thus is in Brooks's report on the iron-bearing regions of Michigan.[1] Conclusive proof of its geological value was given in the mapping of the Penokee area, in 1876, by R. D. Irving of the Wisconsin survey.[2] That area extends for about 60 miles northeast-southwest, and is on the average about 4 miles wide. For the eastern part of the Wisconsin area the outcrops are few, and Irving located the iron formation by magnetic work. Along that belt have been sunk shafts belonging to various mines which have raised quantities of ore, and in no case has a shaft sunk outside of the limit indicated by Irving come upon paying ore.

By means of the dip needle and solar compass, observations were taken which enabled us to trace a curving magnetic formation and connect the outcrops, which were separated by about 16 miles. The same bed was further delimited, and the direction partly checked, by the occurrence, at varying distances along this course, of outcrops of rocks of the underlying formation.

Since the second part of this report contains an exhaustive article on the methods and use of the magnetic needle,[3] the subject is not further treated here. The lines of maximum magnetic disturbance—or briefly, the magnetic lines—are represented on the accompanying general map, Pl. III, by blue lines marked with letters *D* and *E*.

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[1] Magnetism of rocks and the use of the magnetic needle in exploring for ore, by T. B. Brooks. Geol. Survey of Michigan, Vol. I, Part I, 1873, pp. 205–243.

[2] Geol. of the eastern Lake Superior district, by R. D. Irving. Geol. of Wisconsin, Vol. III, 1880, pp. 53–238. Atlas sheets, XI–XXVI.

[3] See Part II, Chapter II, by H. L. Smyth, pp. 336–373.

CHAPTER II

GEOGRAPHICAL LIMITS, STRUCTURE AND STRATIGRAPHY, AND PHYSIOGRAPHY.

GEOGRAPHICAL LIMITS.

The portion of the district here described extends from the north line of T. 47 N. to the south line of T. 42 N., and from the center of R. 31 W. to the west line of R. 33 W., and contains approximately 540 square miles.

Upon the small sketch map at bottom of Pl. III is outlined the portions of the district which have been studied and described by the different authors.

The detail character of the formations is unknown for parts of the area under discussion. This is especially true of the north, west, and southwest parts, where, owing to the readily decomposable nature of the rocks, as determined by the few ledges observed, and to the drift mantle, very few outcrops are to be found.

STRUCTURE AND STRATIGRAPHY.

The Crystal Falls district is not sharply defined petrographically, but is continuous with the Marquette district on the northeast and the Menominee district on the southeast (Pl. I). It is, however, remarkable for the vast accumulation of volcanic rocks, which, while by no means absent from the adjoining districts, do not there play so conspicuous a rôle.

Structurally this district can hardly be better separated from the Menominee and Marquette districts than it can be petrographically. The important sedimentary troughs of the two adjacent districts are separated by an average width of 40 miles. The area between the districts on a direct course is occupied chiefly by Archean rocks, with narrow infolded troughs of Huronian rocks playing a very subordinate rôle. At the east

the Archean is overlain by the sedimentaries of the Paleozoic, the Cambrian, and the Silurian. The connecting Crystal Falls rocks are west of this Archean dome.

In the Marquette district the essential structural features have been shown[1] to be a great east-west synclinorium, upon which more open north-south folds are superimposed. At the western end[2] of the district the superimposed north-south folds become close, and the Republic trough is a close fold with an axis in an intermediate position. In the adjoining Crystal Falls district there are also two sets of folds with their axes approximately at right angles to each other. The closer folds are represented by the great anticline in the central part of the district. This anticline has its axial plane trending west of north and south of east, and the axis plunges down both at the north and south ends.

The more open set of folds at right angles to the above set, is represented by the Crystal Falls syncline, with its axis striking to the south of west, and plunging west. Farther south the axes of the folds become much closer and more nearly east and west, thus nearly according in direction with the close folds of the Menominee district. Thus the structural features of the Crystal Falls district merge into those of the Menominee district, which joins the Crystal Falls district on the southeast, where the great structural feature is a synclinorium similar to that of the Marquette, but with its axis trending north of west and south of east.

A glance at Pl. III will show the presence in the eastern part of the northern half of the district of an oval-shaped mass of Archean, and, nearly surrounding this, a number of rock belts.

The Archean ellipse is 11 miles long and 3 miles wide on the average. The rocks are mainly granite and gneiss. They are cut by rather infrequent acid and basic dikes.

Immediately surrounding the Archean is a quartzose magnesian limestone formation, to which the name Randville dolomite has been given.[3] In the eastern half of the district described by Smyth, where more numerous exposures are found than occur in the western half, the formation has an estimated thickness of about 1,500 feet.[4] Not only are the exposures

[1] Mon. XXVIII, cit., p. 566 et seq.

[2] Loc. cit., p. 570.

[3] See Part II, Chapter IV, by H. L. Smyth, p. 431.

[4] See Part II, Chapter IV, Sec. III, p. 433.

more numerous, but owing to the fact that the strata stand on edge, due to the closer folding of the rock series here, a more accurate estimate of their thickness can be made.

According to Smyth, this limestone formation, in the southeastern end of the ellipse, at its upper horizon becomes mixed with slates, and these increase in quantity until the formation passes above into a slate formation, called the Mansfield slate.[1] This slate formation is found overlying the limestone to the west of the central ellipse likewise, but as few outcrops have been found, it is not positively known to exist as a continuous zone encircling the northwestern end. In a direct line with its probable continuation to the north, a graywacke was found at one place, sec. 19, T. 46, R. 32. This single outcrop is insufficient evidence to warrant the introduction of a graywacke formation as the northern equivalent of a part of the Mansfield slates, and it is probably but a phase of that formation. The only mine of this district producing Bessemer ore is in a deposit in the Mansfield slate.

The close of the Mansfield Slate time was marked by the extrusion of a great series of volcanics, which constitute the next formation in the succession. This volcanic formation has its best and most typical development west of the western Archean ellipse. Because the Hemlock River and its tributaries have exposed good sections in the volcanics, and because this river drains a great portion of the volcanic area, the name "Hemlock formation" is applied to the volcanics. The dip of the flows and of the tuff beds wherever observed is about 75° west. The maximum breadth is about 5 miles. Deducting 15° for initial dip, this would give the enormous maximum thickness of 23,000 feet to the volcanics, upon the supposition that no minor folds occur.

These volcanic rocks have associated with them rocks of unquestionably sedimentary origin, as is shown by their well-bedded condition and the rounding of the fragments. The subaqueous rocks are, however, composed of little-altered volcanic materials, and evidently point to oscillations of the crust during the time of volcanic activity—such oscillations as have long been known to be common in volcanic regions.

Following the volcanics, and overlying them, probably unconformably, comes a series of sedimentary rocks, believed to belong to the Upper Huronian. These comprise chloritic, ferruginous, and carbonaceous slates,

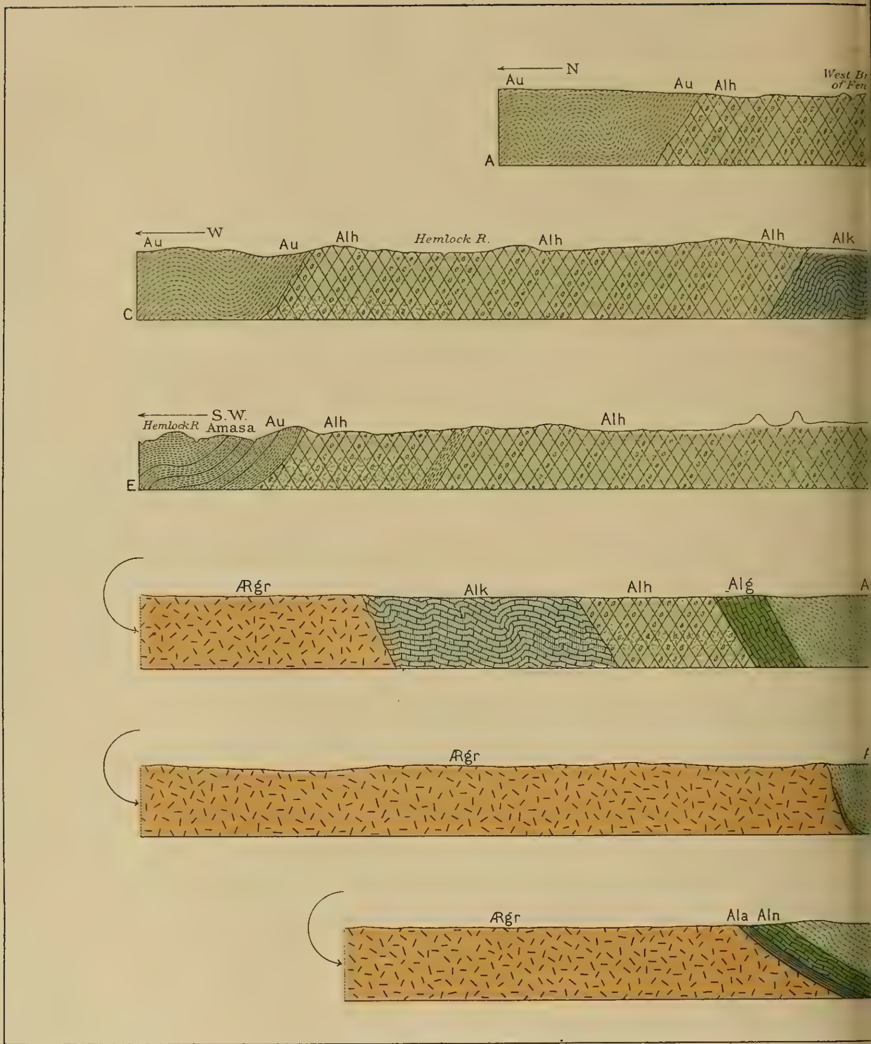
[1] See Part II, Chapter IV, Sec. IV.

associated with quartzites, graywackes, and small amounts of carbonate beds. The general character of the series is what one would expect in rocks the detritus of which was from the Hemlock volcanics. It is in this slate series that, with the exception of the Mansfield mine, the ore deposits of the Crystal Falls district are found. The sedimentaries extend west from the Hemlock volcanics to the limits of the district, underlying thus a very broad expanse of country. Where exposed, they show frequent changes of character. This prevents the identification of individual beds for any considerable distance. Owing to the imperfect exposures of the beds and their close folding, it has been found impossible to subdivide this series of rocks into distinct formations.

The series has in places been highly metamorphosed, resulting in the production of gneisses and mica-schists, in places garnetiferous and staurolitic. The series corresponds in a broad way stratigraphically and lithologically to the Michigamme formation of the Marquette district.[1] Since, however, it has been found impossible to subdivide this series, and because it may possibly include more than the Michigamme formation of the Marquette district, it is considered advisable to speak of it simply as the Upper Huronian series. The generalized sections through the western half of the Crystal Falls district, which are given on Pls. V and VI, will aid in the comprehension of the structural and stratigraphical features thus briefly outlined.

Here and there in the Crystal Falls district isolated patches of Upper Cambrian Lake Superior (Potsdam) sandstone are found. This occurs in beds which are either horizontal or only a few degrees inclined from the horizontal. They overlie unconformably the steeply inclined Huronian strata. The great lapse of time represented by this unconformity is indicated by the deposits of the Keweenawan and Lower and Middle Cambrian time, found elsewhere. The Lake Superior sandstone grades from the very coarse basal conglomerate below into a moderately coarse sandstone above. The sandstone is of a reddish brown to gray color, and is not well indurated as a rule, but is loosely cemented with ferruginous and in places calcareous material. As a result of this imperfect induration, the sandstone is not very resistent to the agents of disintegration. Hence it is that only remnants have been found, but enough is present to indicate that the greater part,

[1] Fifteenth Annual, cit., p. 598, and Mon. XXVIII, cit., p. 444.



JULIUS BIEN & CO LITH. N.Y.

GENERALIZED SECTIONS THROUGH NORTH

HORIZONTAL SCALE, 1 INCH = 1 MILE.

ELEVATION OF BAS

NOTE: Formations are brought to the surface

ARCHEAN

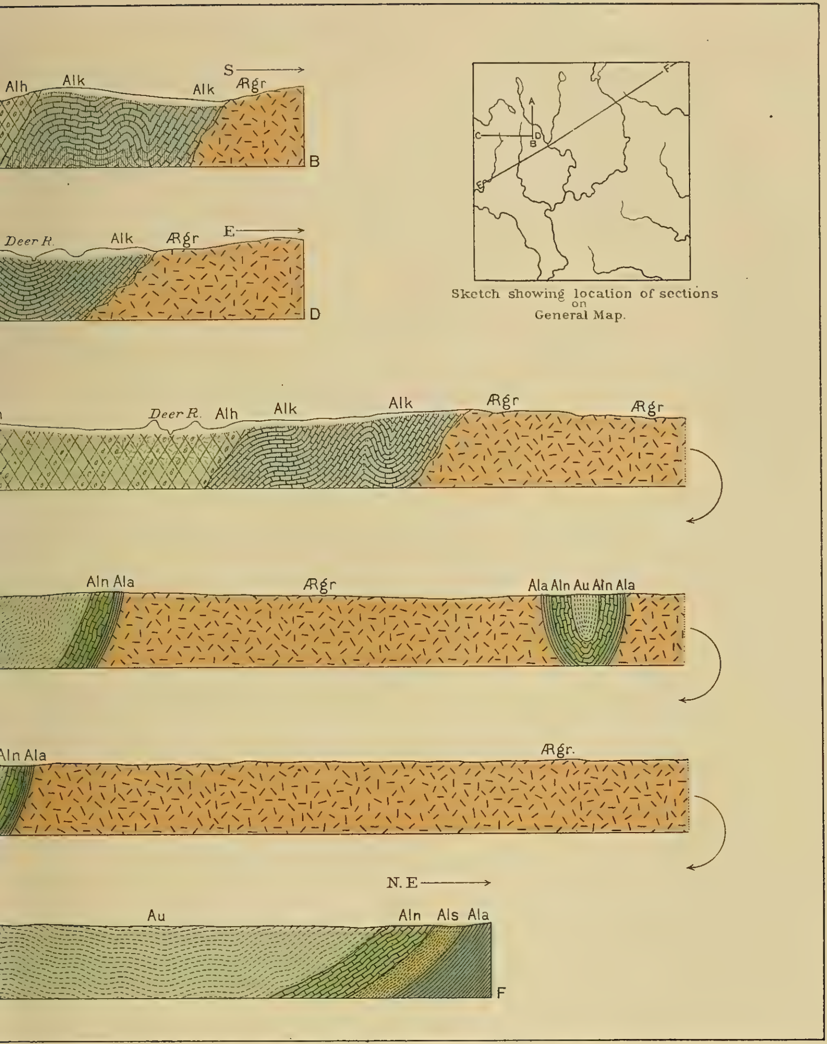
LOWER HU

Ægr — Granite

Als & Ala — Sturgeon and Ajibik quartzite

Alk & Alr — Kono and Randville dolomite

Alm — Mansfi… Siamo…



STERN PART OF CRYSTAL FALLS DISTRICT

VERTICAL SCALE, 1 INCH=1320 FEET.

ES 1000 FEET.

where exposures have been observed.

LGONKIAN

IAN

UPPER HURONIAN

nd
te

Hemlock formation

Groveland &Negaunee formation

Undivided

GENERALIZED SECTIONS THROUGH NORTHWESTERN PART OF CRYSTAL FALLS DISTRICT

HORIZONTAL SCALE, 1 INCH = 1 MILE. VERTICAL SCALE, 1 INCH = 1320 FEET.

ELEVATION OF BASE LINES 1000 FEET.

NOTE: Formations are brought to the surface only where exposures have been observed

ARCHEAN

ALGONKIAN

LOWER HURONIAN

UPPER HURONIAN

Ægr — Granite

Als & Ala — Sturgeon and Ajibik quartzite

Alk & Alr — Kono and Randville dolomite

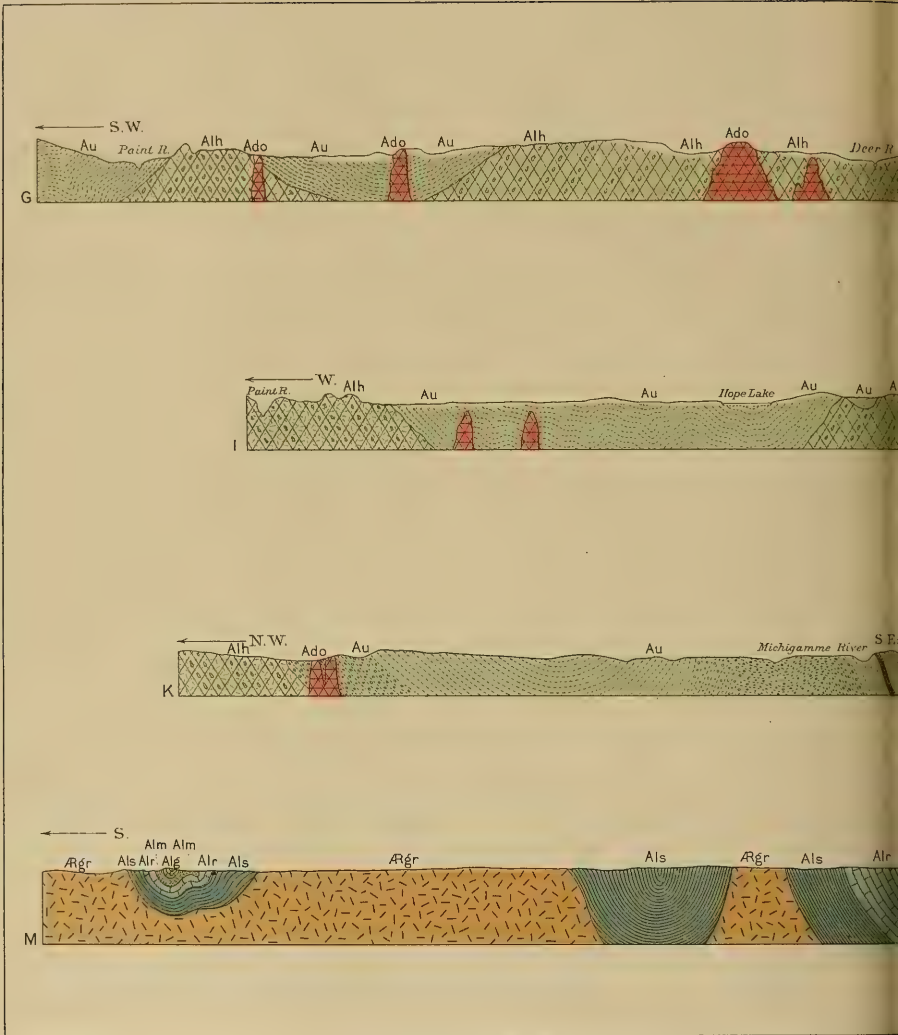
Mansfield and Siamo slate

Alh — Hemlock formation

Alg & Aln — Groveland & Negaunee formation

Au — Undivided

6



JULIUS BIEN & CO LITH. N.Y.

GENERALIZED SECTIONS THROUGH SOU

HORIZONTAL SCALE, 1 INCH = 1 MILE.

ELEVATION OF BAS

NOTE: Formations are brought to the surface

ARCHEAN

ALGON

LOWER HURONIAN

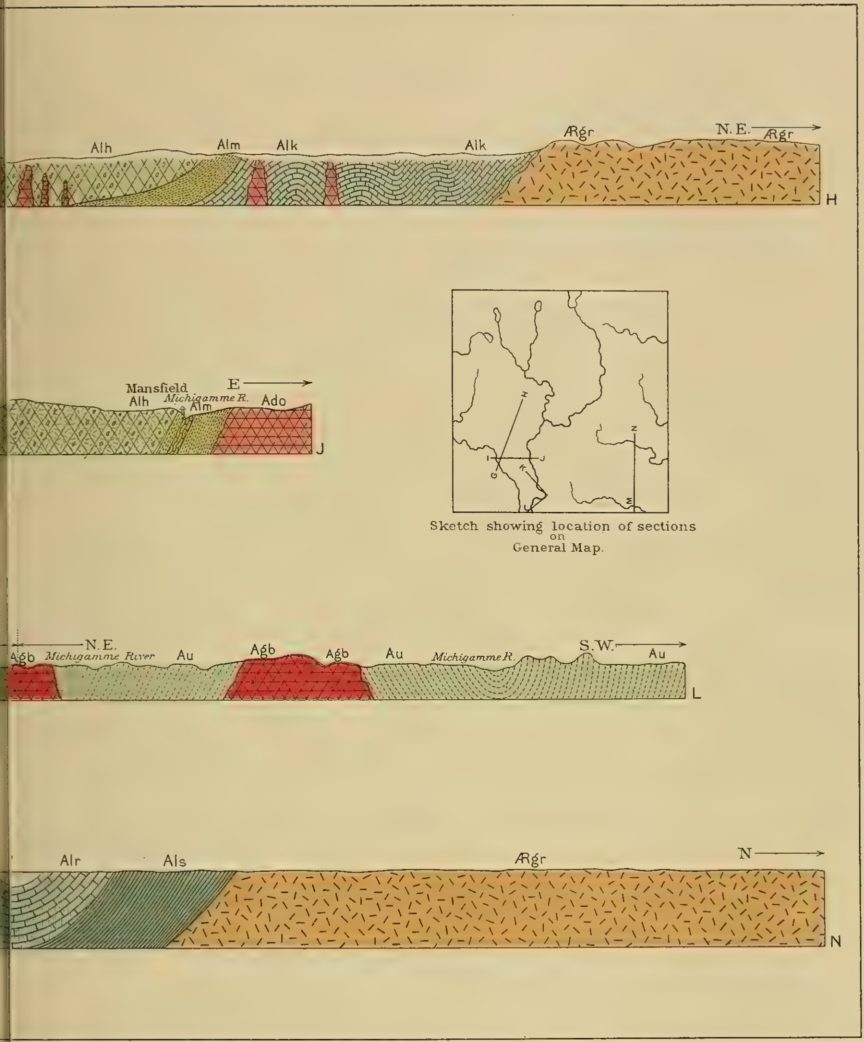
Granite

Sturgeon and Ajibik quartzite

Kono and Randville dolomite

Mansfield and Siamo slate

Hemlock formation



RN PART OF CRYSTAL FALLS DISTRICT

VERTICAL SCALE, 1 INCH=1320 FEET.

S 1000 FEET.

here exposures have been observed.

N

PLEISTOCENE

UPPER HURONIAN

INTRUSIVE

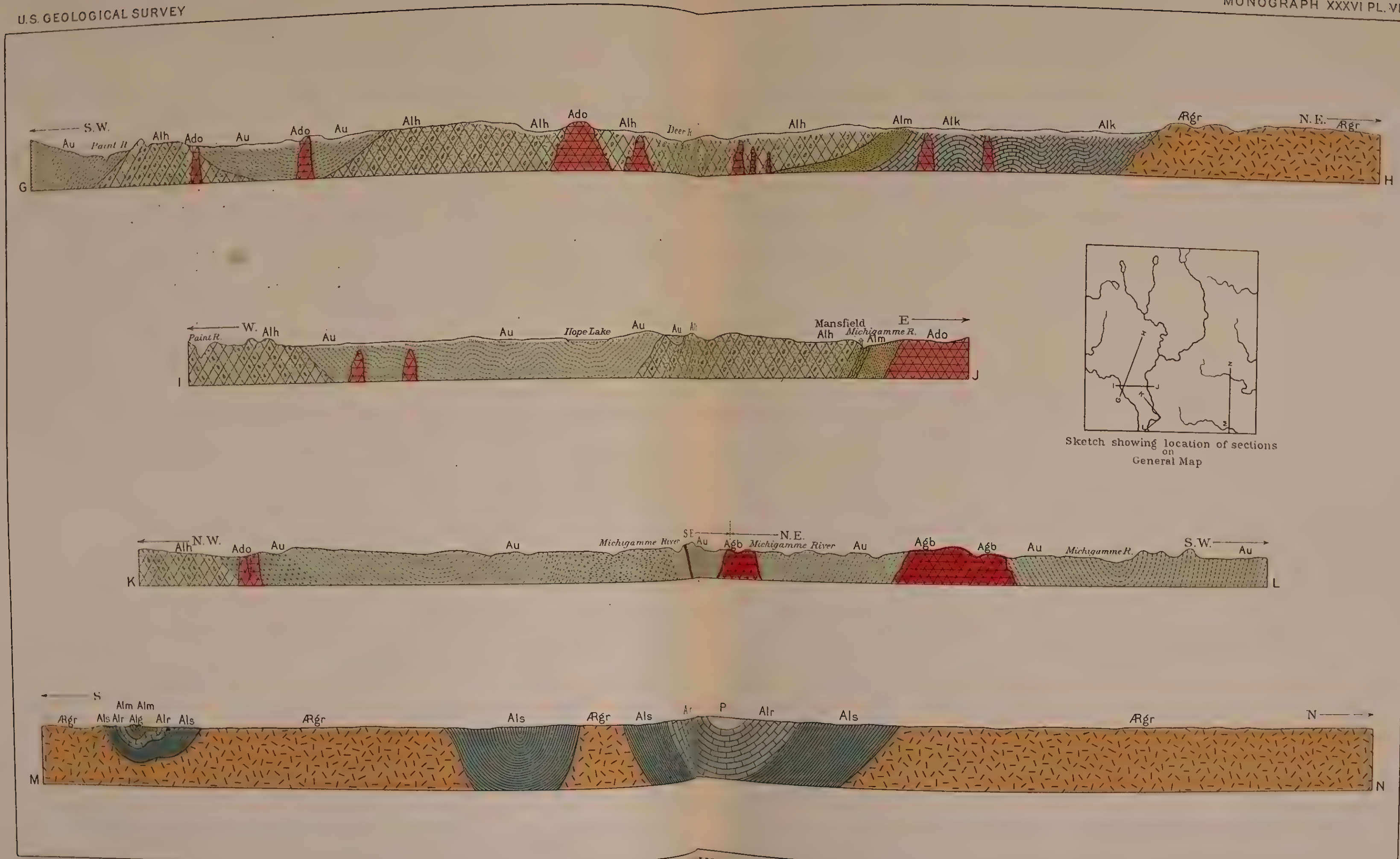
UNDIVIDED

and & Negaunee formation

Undivided

Dolerite

Gabbro



GENERALIZED SECTIONS THROUGH SOUTHERN PART OF CRYSTAL FALLS DISTRICT

HORIZONTAL SCALE, 1 INCH = 1 MILE. VERTICAL SCALE, 1 INCH = 1320 FEET.

ELEVATION OF BASE LINES 1000 FEET.

NOTE: Formations are brought to the surface only where exposures have been observed.

ARCHEAN

Ærg Granite

ALGONKIAN

LOWER HURONIAN

Als & Ala Sturgeon and Ajibik quartzite

Alk & Alr Kono and Randville dolomite

Alm & Als Mansfield and Siamo slate

Alh Hemlock formation

Alg & Aln Groveland & Negaunee formation

UPPER HURONIAN

Au Undivided

INTRUSIVE

Ado Dolerite

Agb Gabbro

PLEISTOCENE

UNDIVIDED

P

and probably the entire Crystal Falls district, was covered by Cambrian deposits. The thickness of the Cambrian deposits can not be determined.

The next higher portion of the geological time scale represented in the district is that part of the Pleistocene period which in this part of the United States is characterized by the past existence of great ice-sheets. The evidences of the existence of the ice are everywhere present, either in the rounding and polishing and scoring on the surfaces of the rocks exposed or in the character of the drift deposits. The direction of the ice movement was clearly from the northeast to the southwest, as is shown by the trend of the striæ, which were observed upon the rounded rock outcrops in various places. The thickness of the drift deposit varies very materially. In places it has been almost entirely removed by denudation, if in such places it ever formed anything more than a thin veneer upon the surface. In other places it reaches a very considerable thickness, as is shown by the glacial topography characteristically developed in T. 45 N., R. 32 W.

As the present report is confined to the pre-Paleozoic rocks, no detail description will be given of these Cambrian and Glacial deposits, nor are they represented on the map, except in those places where it has been found impossible to map the underlying rocks. The generalized columnar section on Pl. VII gives in condensed form our knowledge concerning the formations mentioned.

PHYSIOGRAPHY.

TOPOGRAPHY.

The topography in its large features is pre-Glacial, and in some cases this older topography is rather distinct. For instance, in the case of the Deer River Valley, drift covers the gentle slopes and bottom, but is not sufficiently deep to completely hide the pre-Glacial Deer River Valley.

In the southwestern part of the district west of Crystal Falls, or, more generally, west of the Paint River, pre-Glacial topography is seen in places. Here we find the drift as a veneer and only partly hiding the bed-rock topography, which depends mainly on the strikes, dips, and varying characters of the rocks.

It is so well known that this part of the country was at one time covered by ice, that it is useless to cite such proof as the rounding and

scoring of the rocks and the character of the drift material, a good portion of which can be readily seen to have been brought from some other region, no such rocks as those forming it existing where the bowlders now lie. The ice-sheet left a deposit of drift, and we find the pre-Glacial topography essentially modified by it. As a result of this, the prevailing and most noticeable topography of the western half of the Crystal Falls district is that of the drift, and is characterized by short ridges and broken chains of hills, usually oval, though at times of very irregular outline, between which are lakes and swamps. The swamps are even occasionally found on rather steep slopes, where a thick spongy carpet of moss (sphagnum) retains sufficient moisture for cedars and other trees and shrubs characteristic of the Michigan swamps to grow. The swamps follow the carpet of moss up the hills to the spring line.

The Glacial drift topography is especially marked where the drift was of considerable depth. These conditions are well exhibited in parts of T. 45 N., Rs. 31, 32 W., shown on the large-scale map, Pl. VIII. Here, even though the ground is very heavily timbered, one may easily trace out the sinuous course of the eskers. When traversing the country, one is constantly descending into pot-holes or is climbing ridges, some of them 75 to 100 feet high, often with a crest only a few feet, in some places not more than 4 feet, wide.

Where the drift mantle has been removed, the rounded character of the rock exposures is usually shown. This holds good especially for the more resistant rocks, such as the granites and massive greenstones. Slates and tuffs, weathering more readily, have in numerous cases had time since the ice retreated to be weathered into rough broken ledges, some of which show perpendicular cliffs.

The elevations range usually from 1,400 to 1,600 feet above sea-level. The hills rarely rise more than 200 feet above the low ground at their bases. The extremes of height noted in the district are from 1,250 to 1,900 feet above sea-level, corresponding, respectively, to the valley of the Michigamme on the south and the watershed between Lake Superior and Lake Michigan on the north. Between these two extremes there is a strip of territory, 25 miles across from north to south, in which the variations in height are within the limits of 200 feet.

A consideration of the slight difference of level which prevails over

Period.		Formation name.	Formation symbol.	Columnar section.	Thickness, in feet.	Character of rocks.
Pleistocene.		Glacial drift.				Usual characters.
Cambrian.		Potsdam sandstone.	€p.		?	Thickness unknown. Yellowish to reddish brown sandstone, not thoroughly cemented, therefore disintegrates readily. Found in patches in many places, and always lying either in beds which are horizontal or else possess slight dip to the south. This may represent the initial dip with which the beds were deposited.
Algonkian.	Upper Huronian.	Undivided.	Au.		?	A series of very great but unknown thickness. It consists of alternating beds of slates, graywackes, siderite, and chert. With these, especially associated with the last two, are found hematite and limonite ore bodies of variable size and of great economic importance. From this series is derived nearly all the ore supplied by the Crystal Falls district. In the southern part of the district, especially well exposed in the vicinity of the Paint and Michigamme rivers, the slates and graywackes have been metamorphosed into schists and gneisses. This series is cut by dikes of rock ranging from acid to ultrabasic, which have, in places, metamorphosed the sediments.
	Lower Huronian.	Hemlock.	Alh.		?	The thickness of this vast pile of volcanic ejectamenta can not be estimated with any degree of accuracy. It consists chiefly of interbedded acid and basic lavas and associated tuff deposits, and the water-deposited materials derived from them. Near the top of the volcanics a lenticular area of normal sediments, slates with lenses of limestone, is found. This formation is cut by acid and basic dikes.
		Mansfield slate.	Alm.		1500	Estimated to be about 1,500 feet thick. It consists of interbedded fragmentals, slates, and graywackes and, associated with these, ferruginous chert and carbonate. From these last has been derived the ore found associated with them. The Mansfield mine, by which is exploited the only ore body in the Mansfield formation, supplies the only Bessemer ore of the Crystal Falls district. These slates are cut and metamorphosed by basic dikes.
		Randville dolomite.	Alr.		1500	The thickness is that estimated for this formation in the eastern part of the district by Smyth. The prevailing rock is quartzose dolomite, of a very friable character.
Archean.		Granite.	Ægr.			It shows the usual characters of granite. It is schistose on flanks of massif, and is cut by acid and basic dikes, which are massive and schistose.

GENERALIZED COLUMNAR SECTION.

the greater part of the Crystal Falls district has led Smyth to the conclusion that this portion of Michigan had before Glacial times been reduced to the condition of an approximate peneplain. (See Part II, Chapter I.) This peneplain is a continuation of the peneplain of northern Wisconsin, and lies between the northern Michigan base-level on the north and the central Wisconsin baselevel on the south, to both of which attention has recently been called by Van Hise.[1]

DRAINAGE.

The greater heights in the Michigamme district are in the northern part, where some few of the hills rise to a height of 1,800 feet, and one to a maximum of 1,900 feet above sea-level; but the majority do not rise above 1,600 feet. The belt including these higher elevations extends about NE–SW. This belt represents the crest of the watershed, from which all streams on the northern side flow to Lake Superior, and on the southeastern side all flow to Green Bay of Lake Michigan. A part of this watershed is undivided, and it is not uncommon to find extensive swamps in which streams flowing to opposite sides of the watershed take their origin. The portion of the Crystal Falls district which is tributary to Lake Superior is so small that it will be totally neglected in the further discussion of the drainage. The topographical map, Pl. II shows the general slope and drainage of the district to be SSE. The eastern part of the district is drained by the Michigamme[2] River with its tributaries, the Fence (Mitchigan), and the Deer, while the Paint (Mequacumecum) River, with its main tributaries, the Hemlock and the Net, drains the west and northwestern portions. The Brule (Wesacota) flows along the southern part of the district, being for the most part just below the southern limits of the present map. It forms throughout its course the boundary line between Michigan and Wisconsin. The Paint flows into the Brule in sec. 12, T. 41 N., R. 32 W., and the Brule and the Michigamme unite in sec. 16, T. 41 N., R. 31 W., to

[1] A central Wisconsin base-level, by C. R. Van Hise: Science, new ser., Vol. IV, 1896, pp. 57–59, 219. A northern Michigan base-level: ibid., pp. 217–220.

[2] The Indian names which the streams and lakes of this district formerly bore have either been dropped or else, in a few cases, have been replaced by translations, though most commonly they have been replaced by English names, which are altogether new. Those names which have been retained receive various spellings at the hands of different authors, and even at the hands of the same writer. The Michigamme River, for example, is frequently spelled by Burt in the same article *Peshakumme* and *Pesh-a-kem-e*. The name Michigamme is also spelled on various maps *Machigamig* and *Michigamig*. Whereas the Paint we find spelled *Mequacumecum*, as above most commonly, though Burt spells it *Mesquacumecum* and also *Mesqua-cum-a-cum*.

form the Menominee River. This last flows southeast through the adjoining Menominee district, and is the boundary line between Michigan and Wisconsin from its source to its mouth.

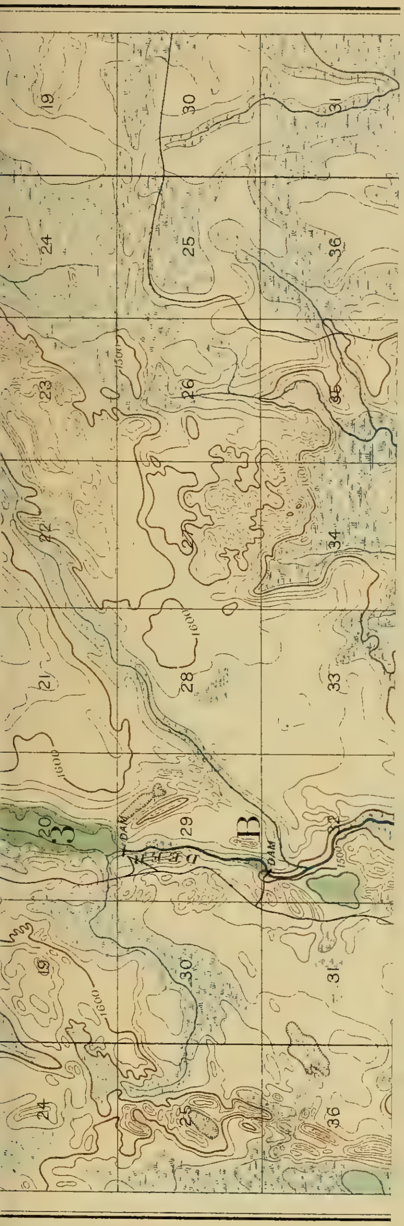
A glance at the map, Pl. II, will show the presence, especially in the northern half of the district, of a great number of lakes of varying sizes. These lakes of clear water, with bottoms of gravel, or most commonly of a thick deposit of decayed vegetable matter, are a very characteristic feature of the landscape. Many are in the midst of swamps, surrounded on all sides by a quaking bog, which prevents one from approaching very closely; others are surrounded by steep but low drift hills. The lakes may or may not have a visible inlet and outlet. In all cases the present water levels are considerably below the original water levels. In many cases the lakes are but remnants of much larger bodies of water. They are gradually filling up with silt and vegetable growth. These lakes, covered with floating lily pads and surrounded by more or less extensive hay marshes, are favorite places for the deer, which in many parts of the district are still fairly numerous. The numerous lakes indicate the youthful character of the drainage. Many of the streams head in the lakes. In other cases they flow through them, connecting them in chains. This indicates the mode of origin of the most of the streams of the area. The youthful character of the drainage is still further shown by the fact that with but few exceptions the rivers have not reached rock. They are still cutting in drift.

In the case of the Deer River this gradual development from the original condition of a chain of lakes to the present condition of a river in which the lakes play very subordinate parts is well shown. Moreover, its development illustrates very well several of the stages passed through by rivers in general, and for these reasons it may be well to describe it in detail.

The life history of the Deer River,[1] as it is to-day, began with the deposit of the drift, which destroyed the former streams of the district and concealed their records. It appears probable from the topography that the river occupies the same, or approximately the same, bed in which its pre-Glacial forerunner moved. The noticeable valley occupied by the stream is at a maximum about 3 miles broad, though its drainage area is a strip averaging

[1] The substance of the following was presented to the Wisconsin Academy of Sciences, Arts, and Letters at the annual meeting, September 27, 1895, in a paper entitled "Some stages in the development of rivers, as illustrated by the Deer River of Michigan." An abstract of the paper was published in Amer. Geol., Vol. XVII, 1896, p. 126.


Prince River
Deer Lake
DAM
DAM
1600
1700



MAP
OF PART OF
CRYSTAL FALLS DISTRICT
SHOWING GLACIAL TOPOGRAPHY
AND
ILLUSTRATING DEVELOPMENT
OF
DEER RIVER

Scale

5 or 6 miles in breadth. The hills between which the stream flows are not very high above the river bed, the maximum elevation being 175 feet. The few rock outcrops are in all cases found on the tops and flanks of these hills, where they have been exposed by denudation. At one point only has rock been found in situ near the river bed, and that is toward the mouth of the river. The conclusion is natural, since the river is 175 feet below these exposed rocks and has not reached rock, that it must be flowing through a preexisting depression or valley partly filled by the drift of the Glacial epoch.

The partial filling of this valley at the time of the retreat of the ice to the northeast was accompanied by the filling of the depressions in the drift by the water flowing from the front of the melting glacier. After the depressions were filled, the overflowing water naturally followed the general southeastern slope, which exists throughout the area and is shown by the topographical maps and by the flow of the rivers. The immediate course of the water was determined by the former valley, which was not completely obliterated by the drift deposit. Drift barriers across the valley separating the ponded water, or lakes, from one another were cut through, the material eroded being spread over the bottoms of the lakes below. Thus was formed a chain of lakes, connected usually by narrow streams; the processes by which the channels were cut out and the lakes drained and filled up with the débris were going on at the same time. The result has been to obliterate the lakes to a great extent and to accentuate the character of the stream.

The final effect of the processes, briefly outlined, would be to destroy the lakes entirely and produce a stream.

By following on Pl. VIII the Deer River from its mouth to its source, we may see the several stages in its development, which are also typical for other streams of the glaciated portions of the world. The river is about 20 miles long and has a width near where it enters into the Michigamme of 20 to 30 yards. Near its mouth it is a slow-flowing, sluggish stream, which has nearly reached its base-level of erosion, and like many of the older streams of the Coastal Plain region of the United States is gradually filling portions of its channel with the silt and vegetable matter brought down from above.

A short distance from its mouth it resembles such streams also in the

meandering character of its channel. This resemblance is still further enhanced by the presence of a remnant of a crescent-shaped cut-off, so characteristic of the old age of rivers. Just opposite this cut-off is a lake, which is of interest on account of its possessing two outlets, both leading into the river. Unfortunately this fact was observed on the topographical sheet too late to permit of a return to the field for the purpose of determining the cause of the presence of the two outlets.

Passing up the stream we soon reach the lakes, which farther on become more numerous. The life history of these lakes is inseparably connected with that of the river. They reached maturity during or at the close of the Glacial epoch, and since that time their history is that of decline. This part of the history of these lakes may be briefly stated as follows: As the erosion continues, the areas of water are reduced and the surrounding swamp areas are correspondingly increased. If a lake were large and considerable inequalities existed in its bottom, two or more small lakes connected by the stream flowing through them may be formed. The final stage is a swamp, traversed by the slow-flowing river.

The various stages in the history of the lakes are well illustrated on the accompanying map, Pl. VIII, by the following series of lakes. In Nos. 1 and 2 the general character of such bodies of water, which may be considered essentially as mere expansions of streams, is seen. No. 3, and Deer Lake, have long since reached maturity and are advancing rapidly to the point where they will each be separated into two bodies of water. No. 4 has already reached this stage, and in the swamp marked A we have the last stage, the swamp, with the stream flowing between peaty banks.

On Light and Liver lakes, in the lower part of the Deer River, we may see all but the last of these stages illustrated. The lakes are attached to the main river by very short streams. The main river after leaving the rapids above, where it accumulates considerable detritus, enters a flat portion of its course partly occupied by the two lakes in question. Here, its rapidity being diminished, the stream deposits the detritus. Thus it has gradually built a delta, now for the most part covered by swamp growth. This tends to advance the shore line, and thus diminish the water area. The rapid cutting down of the barrier immediately below the lakes by the swiftly-flowing stream tends to lower the lakes and thus diminish their surface area still more.

The combined effect of the draining and filling has been to separate what was formerly a long narrow lake trending NE-SW. into three rounded bodies of water, two of which are connected with each other, the larger of these two and the third lake being connected with the main stream by very short necks. An artificial dam has been built across the narrow channel below the lakes, and the effect has been to flood the delta and unite the lakes into one large body of water, occupying, approximately, the area covered by the glacial lake, thus restoring the conditions which existed before the natural barrier had been trenched.

In the remainder of the course of the Deer River the tendency of other artificial dams to restore the river to its original condition, that of a series of connecting lakes, is well shown. These dams were built by lumbermen at the foot of the lakes or swamps when it was desired to retain a large body of water at these places. When, on the other hand, the desire was to enable the logs to pass rapids, a dam (marked *B* on the map) was built near the head of the rapids. The back water would bring the logs to the dam, and on opening the gates the flood would carry them over the rapids into the deeper water beyond. The Deer River thus, after having reached a somewhat advanced stage, has been rejuvenated by the Michigan lumbermen.

A study of the small tributaries shows the same condition of things, although not on so large a scale nor so perfectly as in the main stream.

The source of the Deer River is in the copious springs which rise out of a spongy, marshy piece of ground less than 125 yards distant from Bone Lake, and about 20 feet below the usual water level of Bone Lake, and are really fed by the lake water percolating through the drift and appearing at this point. From the springs there is a depression which leads up to the lake. The highest point of this depression was about 3 feet above the normal water level of the lake.

The outlet of Bone Lake is the Fence River. The river leaves the lake at a point three-quarters of a mile distant from the head of the Deer River Valley. In order to obtain a supply of water for driving the Fence River, Bone Lake has been converted into a reservoir. A dam was built at the outlet which raised the water about 4 feet, and the result was to turn some of the water of the lake into the Deer River, necessitating also a dam across this small valley near the lake shore. At present only a few strokes of the shovel would be necessary in order to turn the water of the flooded

lake from the Fence into the Deer River, thus gaining for it a drainage area extending 7 miles farther north and including three large lakes, the main sources of the water supply of the western branch of the Fence.

I have no data which would enable me to show that the valley at the head of Deer River was ever a channel for the waters of Bone Lake. I am inclined to believe that such was not the case. For had it existed with the present slope, 20 feet in 375 feet, or even a much lower one, the water would have had a marked erosive power, and it would have cut back its channel much more rapidly than the Fence, which for a mile below the lake is a comparatively sluggish stream, and would have eventually captured Bone Lake and its feeders.

The Deer River is still continuing the process of lengthening its channel, and the springs which give it birth are gradually undermining the barrier at its head, so that it is possible that it will, unless artificially restrained, obtain much more water from Bone Lake than it does at present. A change in atmospheric and other conditions, which would insure a state of equilibrium between the incoming and outgoing waters, thus preserving the waters of Bone Lake at their present level, would be favorable for the final successful robbery of the upper Fence River system by the Deer River. This favorable condition, as may be readily seen, would be greatly increased in proportion as the increase of inflowing over outflowing water raised the level of the lake.

TIMBER AND SOIL.

The district was at one time very heavily timbered, with hard wood and pine, the former predominating on the whole. Along the flood plains of the large streams one finds sandy pine barrens where once there were heavy pine forests. On the headwaters the pine are found scattered through the hard wood. Individually these trees are very much larger and better than the thick and therefore smaller growth of the plains. Lumbering, which had been confined for years to the main drainage channels of the district, has of late been rapidly extended, following all the ramifications of the tributary streams, until at present there remains in this district only a few years' cut of pine at the very headwaters of the rivers. Following the lumbermen comes the forest fire, which finds its most nourishing food in the dry resinous pine tops left by them. The fires, once started,

are not confined, however, to the cut pine, but spread to the adjacent standing pine and even into the hard-wood forests, carrying destruction with them, and leaving but the gaunt, bare, and blackened trunks to mark the sites of what were formerly thick forests.

The pine-covered areas have a thin soil and are poorly adapted to agriculture. The areas covered with hard wood have, on the contrary, soil well adapted to the crops of the latitude.

The advance of the lumberman has necessitated the damming and clearing of streams and the blasting of channels to permit the floating of the logs, and this has driven the fish, especially the speckled trout, which formerly crowded all the streams, into the smallest and most inaccessible ones. Ruffed grouse, *Bonasa umbellus*, and deer are still rather plentiful in certain portions of the area, although the pot-hunter with set guns, spring nooses, and pitfalls is rapidly exterminating them. The deadly character of such appliances is brought vividly to mind, when, as happened in my own case, one is suddenly arrested, while following a deer trail through the underbrush, by a hay wire noose around his neck, and he may be thankful if the bent sapling, having been bent so long as to lose its elasticity, fails to spring up and render the device effective.

CHAPTER III.

THE ARCHEAN.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The granite described in this chapter belongs to the oldest system in the district, and forms the western elliptical core designated on Pl. III as Archean. It is surrounded by sedimentary strata, which have a quaquaversal dip away from the granite as a center. The portion of the Crystal Falls district, in which the granite outcrops, is about 13 miles long by 3 miles wide, its longest axis extending in a NW. and SE. direction and covering parts of Ts. 44, 45, and 46 N., Rs. 31 and 32 W.

The exposures of granite are especially numerous in the southeast part of the oval area, where, owing to the proximity of large streams, the Fence and Deer rivers, and the consequent increased erosion, the drift has to some extent been removed. In the northwest part of the area, with rare exceptions, all the rocks are deeply covered with drift.

In general the topography of the area is that of the drift, but in the southern part it is seen to have been considerably influenced by the character of the underlying rocks. The granite usually outcrops in small, rounded, and isolated knobs, whose relations to one another can only be conjectured. Where an occasional knob is composed of massive granite and more or less gneissoid granite, the exposed surface is so small as to prevent the observer from determining the relations between the two. Cutting the massive and schistose granite are certain long narrow masses of dark-colored rocks of rather fine grain, and, with few exceptions, very schistose. From their geological occurrence it was concluded, in spite of their appearance, that they are dike rocks cutting the granite. The following paragraph, quoted from the manuscript notes of G. O. Smith, describes very clearly their field occurrence:

> The gaps in this granite ridge seem to indicate greenstone dikes, as here the granite usually has a facing of the greenstone more or less extensive, and often in the center of the gap there are several small areas of greenstone. In all cases the

greenstone is markedly more affected by weathering than is the granite. A study of the relations at the few points of contact did not yield much more than negative results, but these pointed to the intrusive character of the greenstones.

RELATIONS TO OVERLYING FORMATIONS.

The relations of the granite to the sedimentary rocks might be explained in two ways; the former may serve as the base of the latter rocks, or it may penetrate them. The occurrence of the granite in an elliptical shape, with sediments surrounding it showing quaquaversal dips, might be regarded as evidence of its intrusion in the Huronian sediments, and on this theory it would follow that the granite is of Huronian or post-Huronian age. If intrusive, it should be found to penetrate and metamorphose those sediments. Against the intrusive character of the granite, and in favor of its pre-Huronian age, are the following facts: (1) There is a total absence in the surrounding sedimentary strata of any dikes which are related to the granite. (2) There is a total absence of any metamorphic action, so far as observed, in the sedimentaries. (3) On the east flank of the granite core, on the west bank of the west branch of the Fence River in the SW. corner sec. 1, T. 45 N., R. 32 W., is a recomposed granite, which passes up into a fine sericitic quartzite, with false bedding. These rocks evidently derived their material from the granite, and hence mark the beginning of sedimentation in this area.

Thus the positive evidence confirms the negative, and since the granite underlies the oldest sedimentary rocks, whose age has been determined to be Huronian, the former is classified as Archean, that term being used here to designate those rocks of undoubted igneous character which form the foundation upon which rest the oldest determinable sedimentary rocks. It is not the province of this paper to enter into a speculative discussion of the origin of the Archean rocks of the district. For such a discussion the reader is referred to Professor Van Hise's exhaustive disquisition on the Principles of North American pre-Cambrian Geology,[1] where the conclusion is reached that "the Archean is igneous and represents a part of the original crust of the earth, or its downward crystallization."[2] The Archean has gradually reached the surface by the removal by erosion of the superjacent rocks.

[1] Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 571-874.
[2] Loc. cit., p. 752.

PETROGRAPHICAL CHARACTERS.

The rocks of the Archean comprise biotite-granite, gneissoid biotite-granite, and acid and basic dikes.

BIOTITE-GRANITE (GRANITITE).

The rock occupying the main and central part of the Archean area is a biotite-granite. This rock is also found to some extent on the border of the area. The rocks of this kind vary in color from light-gray rocks to those having various tints of red, depending usually upon the degree of alteration. They vary also from medium to coarse grain. Some varieties show a decided porphyritic texture, and in some cases also an approach to a laminated structure. The porphyritic character is due to the presence of large crystals of feldspar, which stand out from the surrounding granitic groundmass, thus producing a typical granite-porphyry. The feldspar phenocrysts lie with their longer axes parallel, and thus help to produce an imperfect laminated structure. This parallel structure in the granite-porphyry is apparently analogous to the flow structure of the volcanic rocks, and probably was produced by movements in the magma before it had reached even a viscous state, as we find that the phenocrysts give no evidence of having undergone excessive mashing or torsion. The different textural varieties grade into one another in such a way as to indicate that they are merely modifications of the same magma. In addition to these textural varieties, which are original, we find in certain places a passage from massive to schistose rocks, in which the schistosity is of dynamic origin, i. e., of secondary nature.

In the thin sections these rocks show the normal granitic texture and the usual mineral constituents which characterize biotite-granites. The chief minerals are orthoclase, microcline, plagioclase, quartz, and biotite. Zircon and apatite are the accessory minerals present, and the secondary minerals include epidote-zoisite, chlorite, muscovite, rutile, and iron pyrites.

Quartz occurs in grains forming the cement and molding around the other minerals. In one of the granites it has a peculiar saccharoidal character macroscopically, and under the microscope such portions are resolved into very fine aggregates of quartz grains.

The quartz is also frequently found in round blebs of varying size included in the best crystallized feldspar crystals. Thus the crystallization

of the quartz, unless such quartz represents the "quartz de corrosion" of the French authors, continued through the entire time occupied by the crystallization of the feldspars, since it is included in the oldest feldspar of the rocks, and also forms the matrix in which lie the youngest feldspars. Undulatory extinction, so general in the quartzes, shows that the rocks have been subjected to pressure, and in some cases it has been sufficient to produce the extreme cataclastic structure of very greatly mashed rocks.

The quartz includes numerous gas and fluid inclusions, the latter frequently with dancing bubbles and forming negative crystals, by means of which it is easy to orient the irregular grains. The quartz of one of the specimens was found to contain liquid inclusions, each of which, besides the usual bubble, held a small rectangular crystal. These crystals are transparent, with a light greenish tinge. A crystal similar in appearance found in the same quartz individual is partly inclosed by a large U-shaped bubble, and gave inclined extinction, though no further optical tests could be made upon it.

Three kinds of feldspar are present: (1) A finely striated plagioclase; (2) a feldspar, unstriated, or at most showing Carlsbad twins, and presumed to be orthoclase; and (3) microcline, these last two being frequently intergrown after the manner of perthite. The plagioclase was the first feldspar to crystallize. It is invariably so altered that the twinning laminæ are nearly obliterated, thus preventing accurate measurements. It is probably oligoclase; and if so, it is highly probable that much of the white mica produced by its alteration is paragonite instead of muscovite, a fact not determinable microscopically. The phenocrysts are orthoclase, usually in Carlsbad twins, and thus at first sight appear to have been the first feldspar to crystallize; but I find that these phenocrysts not uncommonly inclose small rectangular, more or less automorphic,[1] crystals of plagioclase, which is in reality the oldest feldspar. Hence these orthoclases, notwithstanding their porphyritic character, are later than a part of the plagioclases. One phenocryst with Carlsbad twinning was observed in which one part of

[1] Automorph, Xenomorph; Über die Eruptivgesteine im Gebiete der Schlesisch-Maehrischen Kreideformation, by Carl E. M. Rohrbach: Tsch. Min. Pet. Mit., Vol. VII, 1886, p. 18.

Idiomorph, Allotriomorph; Rosenbusch: Mik. Phys., Vol. II, 1887, 2d ed., p. 11.

L. V. Pirsson has recently proposed in a paper, read before the Geological Society of America, on A Needed Term in Petrology, the term anhedra for minerals which do not possess crystallographic outlines and are xenomorphic, in contradistinction to those which we properly call crystals and which are automorphic: Geol. Soc. Am., Vol. VII, 1896, p. 492, and Am. Jour. Sci., 4th series, Vol. II, 1896, p. 150.

the individual shows microclinic striations. The other part was untwinned, and near the center of the phenocryst, bisected by the Carlsbad twinning plane, was found a rectangular plagioclase crystal.

The microcline is usually the best crystallized feldspar in the groundmass, and also by far the freshest. In the few cases in which it was observed in contact with plagioclase, the latter molded it, and is therefore older than the microcline, which in its turn is older than the orthoclase. In one case a microcline individual showing the lattice structure over a portion of its surface possesses no twinning lamellæ in another portion, the twinning lamellæ fading until they totally disappear. Thus no sharp delimitation is apparent between the twinned and untwinned portions of the individual.

In most slides all the feldspars are much altered, but even in those in which the microcline is fresh the plagioclase and orthoclase always show alterations, the plagioclase altering most easily and usually being so changed that it is with difficulty that one can recognize the twinning lamellæ. Hence some of them may have been taken for the nonstriated orthoclase. In an early stage of the alteration of the feldspars minute dark ferrite particles which impregnate them are hydrated, and this gives the feldspars a more or less distinctly red tinge. In a more advanced stage of alteration, muscovite and a little epidote-zoisite are produced. Another alteration of the feldspar is always associated with marked pressure phenomena, and hence is presumed to be the result, partially at least, of dynamic action. This is the partial or complete granulation of the feldspar and the production from that mineral, with the addition from other sources of the iron and magnesia necessary, of secondary white mica and quartz, and some biotite. It is highly possible that some of the small limpid grains considered to be secondary quartz are really an acid feldspar. Orogenic movements are also indicated by the bending of twinning lamellæ, and were probably the partial cause of the twinning.

Biotite occurs in plates, and as a rule shows better-developed crystals than does the feldspar, though it frequently occurs in decidedly ragged flakes. It is strongly pleochroic, showing absorption in the following colors: Pale straw yellow to yellowish brown, for rays vibrating perpendicular to cleavage, to very dark chocolate brown and greenish brown for those parallel to cleavage. In the case of the biotite showing a greenish color this

seems to be the result of incipient alteration, since the edges of the flakes are ragged, and in many cases almost the entire biotite of the section is altered to a chlorite, which shows ordinary white to light greenish pleochroism, with the simultaneous production of epidote and bundles of needles with high single and double refraction, having yellowish or brownish color. These needles are taken for rutile. The biotite is found usually lying between the feldspar and quartz grains almost as though it had been the last product of crystallization. It has suffered crushing with the other minerals.

Apatite and zircon were observed in a few crystals. No original iron ore was seen. As intimated above, by the use of the term "epidote-zoisite" the exact character of this secondary material is not always determinable. In some instances parts of an epidote crystal show the deep blue interference color of zoisite, apparently indicating a mixture of the zoisite and epidote molecules, the latter predominating in the crystals.[1] The remaining secondary minerals mentioned as occurring in the granite show their usual characters.

GNEISSOID BIOTITE-GRANITE, BORDER FACIES OF GRANITE.

About the central area of biotite-granite just described, and in part forming the border of the Archean area, are rocks having a gneissic structure. With these are associated the biotite-granites. The gneissoid rocks in general are markedly darker in color than the granites, showing normally a rather dark gray. They vary little from one another in texture and are much finer grained than the granites. The fine-grained condition of these schistose and banded rocks has perhaps a great deal to do with their dark color, though this is primarily owing to the amount of biotite present.

In some of the specimens the bands can be readily distinguished under the microscope, and are seen to contain a white mica and a much smaller amount of biotite. These two minerals are present in fine films between the crushed quartz and feldspar grains, giving to the rocks a very decided schistose character. These mica folia are much more numerous in certain areas than in others, thus producing a more or less perfect banding. The mica plates are not all regularly parallel, although ordinarily having a

[1] On some granites from British Columbia and the adjacent parts of Alaska and the Yukon district, by F. D. Adams: Canadian Record Sci., Sept., 1891, p. 346.

tendency to this arrangement, and are usually parallel to the banding. The most perfect schistosity is thus developed parallel to the micaceous bands. The banding and the schistose structure are plainly of secondary origin, the result of dynamic action.

Others of the gnessoid granites, however, when examined under the microscope, are decidedly massive, and it is only on a large scale that the banding shows distinctly. In such cases the cause of the banding could not be determined, and might by some be ascribed to differentiation, though, from the association of these gneissoid granites with those just described, it is assumed that the banded structure is due to dynamic action. If this be the case, however, a complete recrystallization has taken place, and slight dynamic effects are now shown. The strike of the banding, wherever it was taken, was uniform, varying from N.–S. to nearly N. 45° W., agreeing, on the whole, with the trend of the Archean oval area.

The microscope shows that the constituent minerals of the gneissoid granites are the same as those which compose the granites just described. These show also the same relations to one another and the same general characters as in the granites, except where mashing has completely obliterated the original texture, and hence no further description of them is necessary.

The crushing to which the gneissoid granites have been subjected is very clearly shown in the present cataclastic condition of the quartz and feldspars.

As stated above, both the gneissoid granite and the granite proper are found in the border area of the Archean. In those rocks in which the contact shows a gradual transition from the banded rock to the unbanded, the micaceous bands are clearly secondary, and are the result of the crushing of the original granite, these lines representing macroscopic and microscopic shearing planes along which the feldspar and quartz have been thoroughly granulated, and sericite and some biotite produced, as was found to be the case also in some of the granites. These rocks thus agree in their dynamic origin with a similar but apparently more extensive and better developed gneissoid border facies in the Morbihan (Brittany) granites, which have been described, and whose origin has been so clearly demonstrated by Barrois.[1] Numerous other similar cases have been described recently from the Canadian granite massifs and from Sweden and other districts.

[1] Ann. Soc. Géol. du Nord., 1887, p. 40.

ACID DIKES IN ARCHEAN.

Observations upon dikes of acid rocks cutting the Archean granite are very few, and we may suppose this to be partly due to their occurrence in isolated knobs, which prevented the determination of the relations of adjacent exposures of rocks of slightly different character. Some few dikes were, nevertheless, observed, and are granites varying from medium to coarse grained, granolitic[1] to porphyritic rocks. The porphyritic facies is the most common. The dikes do not show differences from the main mass of the Archean granite sufficient to warrant detailed petrographical description. The following description of one mass of granite-porphyry is given, as it offers good proof of its relation to the schistose border facies of the granite. In this case the gneissoid rock is found as inclusions in the granite-porphyry, as is illustrated in the accompanying diagrammatical sketch, fig. 4, taken from a ledge in the field. In this sketch the sharply outlined angular and lenticular areas represent the gneiss included in the granite-porphyry. The phenocrysts of this granite-porphyry have a parallel arrangement, the long direction of the phenocrysts agreeing also with the trend of the longer axes of the inclusions. The banding and foliation in the inclusions strike at a right angle to the flowage structure of the granite. The lines of separation between the areas of gneiss and the granite, as shown in this outcrop, are sharp, and point to their nature as inclusions, and such is accepted as the true explanation of their angular character and sharp outlines. As this porphyritic granite was intruded through the border facies of the Archean granite, these fragments were taken up, and were so arranged as to agree with the direction of movement in the intruding mass. This occurrence shows this granite-porphyry to be younger than the great mass of Archean granite, whether we consider the inclusions to be a border facies of the Archean granite, derived from it by dynamic action, and thus of secondary origin, or to have resulted from differentiation of the molten magma.

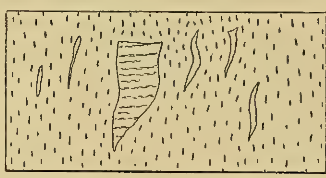


FIG. 4.—Granite-porphyry with inclusions of gneissoid granite.

[1] This term has been proposed by a committee on nomenclature for the geologic folios of the United States Geological Survey, for use in place of "granitic."

BASIC DIKES IN THE ARCHEAN.

The influence of the dikes on the character of the topography has already been mentioned. They occur in long narrow bands of varying widths, and with one exception are markedly schistose. Considering the granite on a large scale as an approximately homogeneous mass, we would expect to find lines of weakness, which might be indicated by the arrangement of the dikes. No such definite arrangement can be seen, however, as the dikes are found to extend in all directions. A good example of their mode of occurrence may be seen in fig. 5, which also illustrates very clearly their influence on the topography. A small valley, in sec. 1, T. 44, R. 32, through which a brook flows, is occupied by the main dike, from which diverge the smaller ones, penetrating the granite on both sides. These, not having been much more deeply eroded than the granite, do not form channels deep enough to be shown on a map with a 10-foot contour interval. It is without doubt owing to the fact that the dikes weather so much more readily than does the granite that we may partly explain the comparative scarcity of exposures. The depressions separating the granite knobs are believed to indicate in many cases the position of dikes, but being now filled with glacial deposits, the underlying dike rocks, if such are present, are covered. Thus we find them exposed only where erosion has cleared this débris away, or where portions of the dike still border the steep sides of the granite on the sides of depressions.

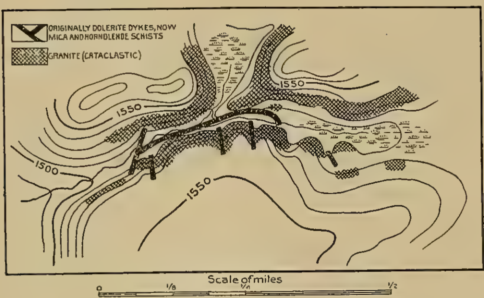


FIG. 5.—Illustration of the effect on the topography of the differential erosion of basic dikes and granite.

The dikes may be classified as (1) earlier dikes, showing a schistose structure, and with no trace of igneous textures, and (2) later massive dikes, showing original igneous textures.

(1) SCHISTOSE DIKES.

The general character of these rocks occurring as dikes may be briefly mentioned. They are schistose, for the most part fine grained, and black

in color. The constituents of the schistose eruptives, arranged according to their relative importance, are biotite, hornblende, chlorite, quartz, feldspar (?), calcite, epidote, iron oxide, sphene, and muscovite.

The clear limpid grains which form the groundmass are undoubtedly for the most part quartz. No satisfactory results were obtained in the tests for feldspar, but it is highly probable that some is associated with the quartz. Dark chocolate-brown to light-brown biotite is almost an invariable constituent. In some cases it is accompanied by a little chlorite, which appears not to have been derived from the biotite. In a few rare instances biotite is absent altogether, chlorite taking its place. The biotite and chlorite are usually found between the quartz grains. They have a parallel arrangement, and this gives the rock its schistosity. Biotite and epidote are found included in the grains of quartz of the groundmass. Muscovite is rarely present, but when found is in medium-sized automorphic plates. Ragged pieces of ore, either ilmenite or titaniferous magnetite, and sphene, secondary to these, are found in almost all specimens, and in a few instances iron pyrites was observed. Calcite is invariably present in irregular, fairly large grains, almost equaling the quartz in quantity. Epidote is found in large quantity, both in crystals and in irregular grains, the crystals occurring among the bunches of biotite and included in the grains of quartz. The large amount of epidote in association with the calcite seems to point to the very basic character of the feldspar of the original rock.

A bluish-green hornblende is rather frequently associated with the mica. In rocks in which the hornblende predominates mica is always present, but the reverse is not true, the most micaceous rocks being entirely free from the hornblendic component.

The hornblende is found in large prismatic individuals without terminal faces. This mineral contains some of the other constituents of the rock in which it is found, such as quartz, epidote, and more rarely iron oxides. The interspaces between the hornblende crystals are filled with irregular biotite flakes and with grains of quartz, epidote, and iron oxide. This hornblende is apparently one of the last, if not the last, mineral to develop. The hornblendic rocks are not nearly so schistose as the micaceous ones.

The secondary origin of the hornblende is clearly shown in one of the sections which is traversed by a fissure; the hornblende can be seen extending into, and in places crossing, this fissure. The other minerals are

presumed to be secondary, but this can not be proved for them. The schistose character of the rocks is evidence of dynamic action. The presence of undulatory extinction was noticed in the quartz of some specimens, but its absence is the rule. However, from the absence of great pressure phenomena, and the remarkably fresh condition of the minerals composing the basic rocks, which contrasts strongly with the generally altered condition of the minerals of the more refractory acid rocks including them, it would appear that complete recrystallization has occurred.[1]

The schistose structure can undoubtedly be referred to the dynamic action which resulted in the upturning of the sedimentaries and caused the development of schistosity in certain portions of the border of the granite. This dynamic action was in all probability also the chief force in the production of the secondary minerals.

The schistosity of the dikes does not agree in direction with the general strike of the schistosity throughout the entire district, but is always nearly parallel to the long extension of the dikes. These dikes represent belts of weakness, and it is therefore natural that the movements should occur along these belts rather than across them.

This schistosity of the dikes also furnishes a slight clue as to their age. Younger than the granites they cut, they must have occupied their present position at the time the dynamic revolution took place which resulted in the development of schistosity in the granite, as well as in the sedimentaries. It is impossible to bring the date of their intrusion within narrow limits. It seems very probable, however, that they were formed at the time of the extrusion of the basic Hemlock volcanics, though it is impossible to prove their connection with them.

(2) MASSIVE DIKES.

The only dike rock which retains to some extent its original texture is a much-altered medium-grained dolerite (diabase). The alterations it has undergone are those usual for such basic types of rock, and this one exhibits nothing peculiar or of special interest. An ophitic texture, while still recognizable, is more or less obscured by the uralite which has developed out of the pyroxene. The remnants of the original plagioclase feldspar present show exceedingly slight pressure effects. The alteration processes would

[1] Principles of North American pre-Cambrian Geology, cit., pp. 706-707.

therefore seem to have been due to the action of percolating water, without special mechanical influence. Hence we may date the intrusion of this particular dike after the orogenic movements which affected the granite core, rendering portions of it schistose, and crushing all of it to a greater or less extent. These movements are presumed to have taken place just prior to or during Keweenawan time; and therefore the age of this dike is Keweenawan or post-Keweenawan.[1]

RÉSUMÉ.

In the above-described granite massif we have a rock of pre-Huronian age, as shown by its relations to the overlying sedimentaries. It possesses in general a coarse granular, and in places porphyritic texture. Along its border it contains portions which are much finer grained, darker than the rest of the mass, and very well banded. The boundaries between the banded rock and the granite at times are sharp, but frequently are very indefinite. This banded schistose portion is found to be due to pressure, causing the gradual passage from the granular granite to the gneissoid, schistose granite.

One instance of undoubted inclusion of gneissoid granite by a true granite was observed. If the gneissoid granite was derived by pressure from the Archean granite, then the particular granite dike which includes the fragments must be of later age than the great mass of granite of the Archean area.

The Archean is cut by basic dikes of two ages. The earlier ones were rendered schistose, and the production of this secondary structure was accompanied by a total obliteration of the primary igneous texture and the production of a large amount of mica and hornblende. All the dikes were probably injected at the time of the volcanic activity when the volcanics of the higher series were ejected, but no proof of their connection can be produced. They were, however, injected before the folding of the area took place, as shown by their having been rendered schistose by it.

A single dike belonging to the later series was studied. It is massive, and therefore was irrupted after the folding which produced the schistosity in the earlier series of dikes. It belongs probably to a Keweenawan or post-Keweenawan period of eruption.

[1] For a discussion of the orogenic movements which affected the Crystal Falls district, the reader is referred to p. 158 et seq.

CHAPTER IV.

THE LOWER HURONIAN SERIES.

This series is represented in the Crystal Falls district by the following formations, given in order from the base upward: The Randville dolomite, the Mansfield slate, and the Hemlock formation. At the beginning of the deposition of the Lower Huronian series the entire district was covered by the pre-Cambrian sea, with the possible exception of a small island in the Archean area.

SECTION I.—THE RANDVILLE DOLOMITE.

The best exposures of this dolomite are found near the center of the district east of the western ellipse and in the extreme southeastern part of the district in the Felch Mountain range. Both areas are described by Smyth, to whom we owe the name, and the reader is referred to his description on p. 406 and p. 431 for the detail characterization of the formation. It will suffice for our purpose to state that it is a medium-grained crystalline dolomite.

The few outcrops which I shall mention are important as showing the relations of the formation to the underlying rock, but are, petrographically considered, rather exceptional phases of the formation. Hence my description will be brief.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The area in which the Randville dolomite immediately underlies the drift is a continuous zone adjacent to and surrounding the Archean core. The belt varies slightly in width along the sides of the ellipse. At the ends it is two or three times the width at the sides. This is due to the lower dip of the beds at the ends. Exposures are found in the area studied by me only on the northeast and southwest flanks of the granite core.

The west branch of the Fence River follows the limestone area for a short distance in the northeastern part of the district, skirting the Archean

granite. On the whole, however, the Randville dolomite has had no marked effect on the topography or the drainage.

PETROGRAPHICAL CHARACTERS.

In general the Randville dolomite consists petrographically of a fine-grained dolomite, with some quartz. This grades down through a calcareous quartzite by increase of quartz into a true quartzite. The nearer the granite, the more quartzitic is the formation. At the southeast corner of sec. 2, T. 45 N., R. 32 W., on the west bank of the west branch of the Fence River, is a very good exposure of the quartzite. Its derivation from the underlying granite is here shown. The rock is a very fine-grained, almost novaculitic, quartzite. It shows current bedding in some places, though no true bedding was observed. Immediately below this quartzite is a very schistose rock, in which one can readily distinguish macroscopically rounded to lenticular quartz areas, with masses of sericite flakes between them. The contact between the quartzite and the schistose rock seems very sharp when viewed from a short distance, but is found to be indefinite when closely examined. A close search was made along a contact for pebbles from the granite, but such were not found. However, small rounded pieces of vein quartz, most probably derived from the granite, were observed. The schistose rock in its turn grades down into a grayish granite, which is also more or less schistose. We have here evidently a transition from the granite, through the intermediate schistose recomposed granite, to the true sedimentary rock above. The meaning of this transition is considered below.

Under the microscope the cause of the schistosity of the rock intermediate between the granite and the quartzite is plain. Quartz and sericite, with some feldspar, are alone present in it. The quartz is grayish and granulated, and mashed out into oval areas representing original quartz grains. Various fragments constituting the areas are, however, angular and more or less equidimensional, and when not so never have a definite orientation of their longer axes. Between these large areas, but not between the individual small fragments constituting the areas, sericite is abundant. When the sericite is not predominant, the flakes lie in a fine mass of quartz grains, each of which agrees in long direction with the mica plates and large oval quartz areas. The sericite flakes are both included in this quartz,

and also lie between the grains. In one instance fragments of the original feldspar were found in the midst of such an area. These quartz-sericite areas are unquestionably of secondary origin, and the minerals have developed in connection with pressure. They were probably produced from feldspar which existed in the original granite.

Whether this schistose rock was formed from a weathered but not transported granite, from an arkose or feldspathic sandstone, or from the solid granite, it is impossible to say. A similar sericite-schist which developed from recomposed granites has been described by Van Hise as occurring at several localities in the Marquette district.[1] In these cases at places the fragmental characters are still sufficiently clear to admit of the statement that the rocks are sedimentary. In the Crystal Falls rock mashing has destroyed all original characters. The rock occupies an intermediate position between a metamorphosed sedimentary and a metamorphosed eruptive, and grades on the one hand into the sedimentary and on the other into the eruptive. This makes it impossible to say whether it belongs exclusively to the one or to the other, or in part to both. Similar relations in other parts of Michigan were explained by Rominger[2] as cases of progressive metamorphism of sediments, the granite being supposed to be the extreme stage of alteration of the sedimentary rock. Later the finding of basal conglomerates at or near these localities has shown conclusively that this explanation is incorrect, and it has been abandoned by Rominger.

The quartzite, which immediately overlies the rock of doubtful character, is composed of angular grains of quartz, between which are plates of sericite which have an imperfect parallelism, thus giving a certain degree of schistosity to the quartzite, possibly enough in places to warrant its being called a quartz-schist. The rock shows no conclusive microscopical evidence of a sedimentary origin, but differs from the cherts, with which it might be confused, in the size of the grains and in the presence of sericite. This rock was originally probably chiefly composed of quartz sand, with some feldspathic material from the disintegrated granite. Coincident with the pressure which produced the striking schistosity in the underlying rock, this sand was also mashed, resulting in the production of sericite and quartz

[1] Mon. U. S. Geol. Survey Vol. XXVIII, 1897, p. 226.

[2] The Marquette iron district, by Carl Rominger: Geol. of Michigan, Vol. IV, Part I, 1878–1880, pp. 15–52.

from the feldspar and in the crushing of the quartz grains, thus completely destroying the rounded clastic grains and obliterating all the sedimentary character of the rock, except the macroscopic structure of current bedding.

On the west side of the granite ellipse, at N. 1750, W. 1550, sec. 12, T. 44 N., R. 32 W., about 100 yards from the granite, to the north, and lower down on the slope of the same hill on which the granite is found, is found a carbonaceous quartzite or quartzose dolomite. The strike is N. 25°–35° W. The surface only is seen, so that the dip could not be taken. Microscopical examination shows the rock at the eastern side of the exposure to be made up of quartz grains held together by a fine-grained carbonate cement. This grades up to the west by increase of calcite and corresponding diminution of quartz to a quartzose dolomite.

At N. 500, W. 1550, sec. 1, T. 44 N., R. 32 W., one-fourth mile distant from the granite, is seen another outcrop of a very dense quartzose dolomite, appearing macroscopically almost like a vitreous quartzite, but really with just enough quartz grains in it to enable the qualifying term "quartzose" to be appropriately used. The brown ferruginous crust on the weathered surfaces point to a percentage of iron in the magnesium-calcium carbonate. The pure limestones are to be sought slightly farther away from the Archean shore, where the conditions were more favorable for the production of a pure nonclastic sediment.

RELATIONS TO UNDERLYING AND OVERLYING FORMATIONS.

At only the one place cited above has a contact between the granite and the Randville dolomite been found. It is probable that unconformable relations exist, even though no basal conglomerate has been discovered as evidence of wave action on the Archean coast.

Relations between the Randville dolomite and the overlying formations have not been observed in the part of the district studied by me.

THICKNESS.

Reliable data for estimating the thickness of the Randville dolomite have only been obtained in that area surveyed by Smyth. (See p. 433.) According to his estimate, the formation possesses a maximum thickness of 1,500 feet.

SECTION II.—THE MANSFIELD SLATE.

The formation of the Lower Huronian, which is next higher than the Randville dolomite, is composed of sedimentary beds, in which a slate predominates.

This formation is found in its most typical development in a narrow valley through which the Michigamme River flows, and in which the village of Mansfield and a mine of the same name are situated. The valley and the slates are well known in the Crystal Falls district on account of their economic importance. For this reason the name "Mansfield slate" is here applied to this formation.

DISTRIBUTIONS, EXPOSURES, AND TOPOGRAPHY.

The part of the valley occupied by the Mansfield slates begins at the northern section line of secs. 17 and 18, T. 43 N., R. 31 W., and extends due south for 3 miles to the southern section line of sec. 29 of the same township. The slate belt is widest at the north, being over one-fourth mile wide on the westren side of section 17. To the south it gradually diminishes in width, until it finally disappears in sec. 29. The strike of the sedimentary rocks is almost due north-south, except in a few places where the rocks have been gently flexed and the strike varies a few degrees. The dip is high to the west, ranging from 65° to 80°.

The influence of the Mansfield slate belt upon the topography is strikingly shown by the depression in which the slates are found, and which contains the Michigamme River. The slates are surrounded on all sides by igneous rocks which form fairly high hills, those to the west being composed of rocks of volcanic origin, those to the north, east, and south being intrusive, and later than either the sedimentaries or the volcanics. The Michigamme River flows south through sec. 1, T. 43 N., R. 32 W., and meets the east and west ridge of intrusives in the northeastern part of sec. 12 of the same township and range. It cuts through this at an oblique angle, changing its course to the southeast In sec. 7, T. 43 N., R. 31 W., it leaves the intrusives and penetrates a short distance into the volcanic rocks, their contact not being able to cause a change in the course of the river, owing to the slight difference in resisting power between the intrusives and the volcanics. Still flowing to the southeast, it finds at

the Michigamme dam, on the section line between secs. 7 and 18, near the southeastern and northeastern corners, respectively, the contact between the three kinds of rock, the sedimentaries, the volcanics, and the intrusives. Where the water leaves the eruptive and enters the sedimentary area the more easily erodible nature of the rocks of the latter is well shown by the falls which have been formed, the volcanics constituting the barrier over which the water plunges into a deep basin worn from the slates. Crossing the slates in the same direction, i. e., southeast, the river strikes squarely against the intrusive dolerites and is deflected to the south, following the contact between the two rocks for a short distance, then gradually working to the west into the center of the sedimentary area, the river takes an almost directly southerly course, with only minor bends. In the slates the river has fairly low flat banks on both sides. In the southern portion of the area the valley is narrower, owing to the progressive narrowing of the sedimentary belt. As soon as the river leaves the Mansfield slate belt, it resumes the sinuous course it had before the Mansfield belt is entered, and flows between high banks through the intrusives, out through the sand plains near Lake Mary.

POSSIBLE CONTINUATION OF THE MANSFIELD SLATE.

In sec. 10, T. 44 N., R. 32 W., about 7 miles northwest of the extreme northern end of the Mansfield area of slate, there are one or two exposures of much crumpled interbedded brown and black slates. Their strike is about N. 16°–20° W., but owing to their plicated condition the dip varies from 55° southwest over to 85° northeast. The average dip, however, is presumed to be to the southwest, which is in accord with the general structure of the area.

The slate exposures are surrounded by coarse-grained basic intrusives, dolerites, which outcrop within short distances on all sides. The nearest sedimentary beds are quartzose dolomite ledges which outcrop 1½ miles to the east, in secs. 1 and 12, T. 44 N., R. 32 W., rather close to the Archean granite. A section across the Lower Huronian rocks at this point shows the Archean granite overlain by quartzose dolomite, which is in its turn overlain by the slates. The relations which these rocks bear to one another are those which similar ones bear to one another near Michigamme Moun-

tain,[1] and the slates of the two areas are consid red to be of the same age. Since the slates correspond stratigraphically to the slates of the Michigamme Mountain and to those of the Mansfield area, they have been connected on the map with the slates of Michigamme Mountain by a narrow belt included between dotted lines; but this belt is not based on any connecting exposures.

These two ledges of slate are taken as the northernmost outcrops of the Mansfield slate formation, although a number of miles north and in direct continuation of them along the strike there was found a single doubtful outcrop of a graywacke, showing neither strike nor dip. Whether it represents a shallower water deposit contemporaneous with the slates it is impossible to say. However, on such slight evidence it was not deemed advisable to continue the slate belt to this point.

PETROGRAPHICAL CHARACTERS.

A petrographical description of the Mansfield slate belt must necessarily be very brief, owing to the small area and to the scarcity of the exposures.

The rocks of the Mansfield slate belt are graywackes, clay slates, phyllites, siderite-slates, cherts, ferruginous cherts, and iron ores, with the various rocks which have been derived from them by metamorphism. They vary from coarse-grained rocks to very fine grained slaty ones. The latter predominate, and for that reason this belt is called a "slate" belt. The color of the rocks varies from an olive green and purplish black to bright red for those which are very ferruginous and more or less altered.

The ordinary detrital rocks may be divided into the coarser and the finer kinds. The first are the graywackes, and the second are the ordinary clay slates and phyllite. There is, however, a gradation from the one to the other.

GRAYWACKE.

The graywackes consist largely of grains of quartz and feldspar of unquestionably detrital origin. Associated with these is a large amount of mica, chlorite, and actinolite, with invariably more or less rutile. This last is in minute grains as well as in crystals. Many of the crystals show fine knee twins, triplets, and more rarely, heart-shaped twins. Tourmaline

[1] See Part II, Chapter IV, Sec. IV, by H. L. Smyth.

is sometimes present. The ferro-magnesian minerals develop chiefly from the alteration of the feldspar, and from the finer detritus which is presumed to have existed between the grains. As a consequence, the secondary minerals lie between the original grains. Many of the quartz grains are enlarged, and here the secondary minerals are included in the new areas of the enlarged grains. In numerous cases the new quartz occupies about as much space as the original grains themselves. This shows very clearly the porous character of the original sandstone. All original grains of the rocks show signs of extensive mashing. Some specimens contain a large amount of tourmaline in long slender crystals, which penetrate both the feldspar and the quartz grains. The presence of tourmaline is especially interesting as indicating that these sedimentaries may have been subjected to a certain amount of fumarole action. According to the proportion in which the various minerals have developed, we obtain sericite-, actinolite-, or chlorite-schists produced from the graywackes.

CLAY SLATE AND PHYLLITE.

The clay slates are dull and lusterless and are black, olive green, or red in color. They are usually impregnated with more or less iron pyrites in large macroscopical crystals. One can distinguish in them quartz, white mica, a few needles of actinolite, rutile, hematite, with a small proportion of a dark ferruginous and carbonaceous interstitial material.

The amount of iron which these clay slates contain varies considerably. In some, hematite is present in such quantity as to cause the slates to be appropriately called hematitic slates. Such, for instance, is the one forming the foot wall of the Mansfield ore body. The iron oxide gives to the slates a very bright red color where they are weathered. These weathered hematitic slates are very commonly known in the district as red slates, or as "paint rock" or "soapstone," though rocks of very different character are also at times designated by these names.

The phyllites have a silky luster and a bluish-black color. They are composed essentially of white mica quartz, some feldspar, innumerable minute crystals of rutile and dark ferruginous specks. These seem to differ from the rocks called here clay slates only in that they are more completely crystalline, the interstitial material of the slates having disappeared.

ORIGIN OF CLAY SLATE AND PHYLLITE.

The origin of the clay slates of the Mansfield formation is probably to be looked for in the disintegration and decay of the Archean granite, and the subsequent metamorphism of the resulting clay. For between the granites and the slates no other rock masses are known to have existed from which the clay could have been derived. The phyllites are presumed to have resulted from the metamorphism of the clay slates.

PRESENT COMPOSITION NECESSARILY DIFFERENT FROM THAT OF ROCK FROM WHICH DERIVED.

It is a well-recognized principle of rock weathering that in the alteration of rocks near the surface of the earth there is a relatively rapid diminution in the quantity of the more soluble constituents. Hence a clay shows a lower percentage of alkalies and alkaline earths than is found in the parent rock, with an increase in the percentage especially of alumina and water. This relation is made clear by Adams in a statement of the comparison of the composition of certain slates and granites:[1] "On comparing the analyses of a series of granites with those of a series of slates, as, for instance, those given in Roth's 'Gesteins Analyzen,' the latter are seen to be on an average considerably higher in alumina and much lower in alkalies, while at the same time they are lower in silica, which has been separated both as sand and in combination with the alkalies which have gone into solution, and in most cases contain more magnesia than lime instead of more lime than magnesia, as is usual in granites." Adams concludes further, after a comparison of the alkalies in the slates and granites, that "The slates thus contain on an average about two-thirds of the amount of alkali present in the average granite."[2] An examination of series of analyses of granites shows that while the percentages of soda and potassa vary considerably, now the one being predominant, now the other, on the whole in the typical granites the potassa is higher than the soda.[3] This is the relation which we would expect in the case of an ideally pure granite,

[1] A further contribution to our knowledge of the Laurentian, by F. D. Adams: Am. Jour. Sci., 3d ser., Vol. L, 1895, p. 65.

[2] Loc. cit., p. 65.

[3] Zirkel states that in the weathering of granites the soda is much more readily removed than is the potassa: Lehrbuch der Petrographie, Vol. II, 1894, p. 32.

in which no anorthoclase replaces the orthoclase. As a consequence of the easier solubility of the soda, this relation between the two alkalies, soda and potassa, is maintained, and is often made more striking in the clay slates. An average of 31 analyses of clay slates taken from various sources shows two and one-half times as much potassa as soda. In the case of the Mansfield slate this difference has been increased, so that there is ten times as much potassa as soda present.

ANALYSIS OF MANSFIELD SLATE.

Mr. George Steiger, of the United States Geological Survey, has prepared a complete analysis (No. 1 in the following table) of a typical specimen of the Mansfield clay slate. Analyses Nos. 2 and 3 were prepared by W. Maynard Hutchings,[1] and numbered by him Nos. 2 and 5, respectively.

Analysis of the Mansfield clay slate.

Constituent.	1.	2.	3.
SiO_2	60.28	59.28	53.57
TiO_2	.69	....	....
Al_2O_3	22.61	21.85	24.53
Fe_2O_3	2.53	5.80	6.51
FeO	.45		
MnO	Trace.	....	....
CaO	.13	.45	.76
BaO	.04	....	....
MgO	1.35	1.24	1.81
K_2O	5.73	4.13	4.34
Na_2O	.54	1.18	.97
H_2O at 100°	.60	6.25	7.65
H_2O above 100°	3.62		
P_2O_5	.03	....	....
CO_2	None.	....	....
C	.97	....	....
Total	99.57	100.18	100.12

COMMENTS ON ANALYSIS.

That which is the most striking about the analysis is the relative proportion of the alkaline earths, lime, and magnesia, the latter being present

[1] Notes on the composition of clays, slates, etc., and on some points in their contact metamorphism: Geol. Mag., Vol. I, 1894, p. 38.

in the greater quantity. As a rule, in all of the igneous rocks (and to the igneous rocks all clay slates owe their ultimate origin), except in the nonfeldspathic ultrabasic ones, the reverse condition exists, namely, the magnesia subordinate in quantity to the lime. The difference in amount of soda and potassa is very striking and should be noticed, in view of certain points to which attention will be called in subsequent pages. The percentage of alumina is higher than is usual in the clay slates. It will be noticed that considerable water is present, but in consideration of the character of the rock this is to be expected. If anything, the value is rather lower than would be expected, indicating a possible loss of water due to the rock having already undergone some dynamic action. The carbon present is considered as offering trustworthy evidence of the presence of organic life at the time of the deposit of the slates, though no more satisfactory evidence of the existence of life has been found.

COMPARISON OF ANALYSIS OF MANSFIELD CLAY SLATE WITH ANALYSES OF CLAYS.

During the last few years there have appeared in the Geological Magazine, from the pen of Mr. W. Maynard Hutchings, some very elaborate and suggestive articles upon the composition of clays, shales, and slates, and from one of these[1] I have taken two analyses of Carboniferous clays for comparison with the Mansfield clay slate. These two analyses, Nos. 2 and 3, p. 59, are from the very fine grained clays, in which the quartz was not distinguishable with the microscope, and are the analyses showing the highest and lowest percentages of silica. Mr. Hutchings says of his analyses that the samples were dried at 220° F., and that the titanic oxide was not determined but is contained in the silica and alumina. Concerning the clays, he writes:

> From these analyses it will be seen that these clays would be capable, chemically considered, of transformation into very typical "clay-slates." Mineralogically they are clay-slates, having already undergone all, or nearly all, the mineral changes requisite to constitute the normal (unaltered) slates. Nothing more is needed but physical changes, such as compacting, arrangement of mica in a plane, increase of *size* of mica, etc.[2]

The great similarity of these *clays* with the Mansfield *clay slate* is very evident. The only material difference which exists between them is in the

[1] Notes on the composition of clays, slates, etc., and on some points in their contact metamorphism, by W. Maynard Hutchings: Geol. Mag., Vol. I, 1894, p. 38.

[2] Loc. cit., p. 38.

higher percentage of water contained in the clays. This difference is natural, clays usually containing about twice as much water as do the slates.

COMPARISON OF ANALYSIS OF MANSFIELD CLAY SLATE WITH ANALYSES OF OTHER CLAY SLATES.

In the following table there are given, for purposes of comparison with the Mansfield clay slate, analyses of typical clay slates, roofing slates from the Cambrian of Vermont and New York.

Analyses of typical clay slates.

Constituent.	1.	2.	3.	4.	5.
SiO_2	60.28	62.37	59.70	67.61	67.89
TiO_2	.69	.74	.79	.56	.49
Al_2O_3	22.61	15.43	16.98	13.20	11.03
Fe_2O_3	2.53	1.31	.52	5.36	1.47
FeO	.45	5.34	4.88	1.20	3.81
MnO	Trace.	.22	.16	.10	.16
CaO	.13	.77	1.27	.11	1.43
BaO	.04	.07	.08	.04	.04
MgO	1.35	3.14	3.23	3.20	4.57
K_2O	5.73	4.20	3.77	4.45	2.82
Na_2O	.54	1.14	1.35	.67	.77
H_2O at 100°	.60	.34	.30	*a* .45	*a* .36
H_2O above 100°	3.62	3.71	3.82	*b* 2.97	*b* 3.21
P_2O_5	.03	.06	.16	.05	.10
CO_2	None.	.87	1.40	None.	1.89
FeS_2	....	.06	1.18	.03	.04
C	.97	Trace.	.46	....	....
Total	99.57	99.80	100.05	100.00	100.08

a H_2O at 110°. *b* H_2O above 110°.

No. 1. Black slate, Sp. 32497, N. 450, W. 1620, sec. 17, T. 43 N., R. 31 W., Michigan. Analyzed by George Steiger.

No. 2. Sea-green slate, Griffith & Nathaniel Quarry, South Poultney, Vermont. W. F. Hillebrand.

No. 3. Black slate, American Black Slate Company, Benson, Vermont. W. F. Hillebrand.

No. 4. Red slate, three-fourths mile south of Hampton Village, New York. W. F. Hillebrand.

No. 5. Green slate, three-fourths mile northwest of Janesville, Washington County, New York. W. F. Hillebrand.

Nos. 2, 3, 4, and 5 taken from Analyses of rocks and analytical methods, 1880–1896, Clark and Hillebrand: Bull. U. S. Geol. Survey, No. 148. Nos. 2 and 3 are, respectively, C and F, p. 277, and Nos. 4 and 5 are A and D, p. 280.

The strong similarity between the composition of these clay slates is at once apparent, and needs no further comment. The only marked difference between the Huronian clay slate and the Cambrian ones is the higher percentage of alumina present in the former.

SIDERITE-SLATE, CHERT, FERRUGINOUS CHERT, AND IRON ORES.

The two most interesting kinds of rock from the Mansfield slate belt are those known as the siderite- or sideritic slates and the cherts or ferruginous cherts, according to the quantity of iron carbonate and iron oxide present. These alternate with each other, and are found also interstratified with the fragmental slates, and thus there can be no question as to their sedimentary character. The siderite-slates are of a light to dark gray color. They are well laminated, and in some places cleave rather readily along the laminæ, though at other places they break with an almost conchoidal fracture. The weathered siderite slates are covered by a crust of reddish-brown hydrated iron sesquioxide.

Microscopically the siderite slates are composed of siderite, or of siderite and exceedingly fine grained cherty silica. Roundish rhombohedra of siderite compose the purer sideritic portions. If one passes from the pure to the less pure slates, the siderite gradually diminishes in quantity, the silica grains increase correspondingly, and the rock grades into the chert which, in bands, is commonly associated with iron carbonate in the Lake Superior region. As the carbonate alters to the oxide or hydrated oxide ferruginous cherts are produced. The cherts are white to red, depending on the amount of iron oxide present. The manner in which the siderite alters to limonite and hematite, and the various steps of the process have been so well described and beautifully illustrated in Monograph XXVIII, that the reader is referred to that volume for further information. None of the brilliant red jasper or jaspilite, such as that found in the Marquette district, is associated with the Mansfield slates. Iron ores of economic importance, however, are found associated with these slates, and are described in detail farther on. None of the sideritic slates, ferruginous cherts, or ores, although interbedded with the fragmental slates, show any evidence of fragmental origin so far as the individual grains of the minerals composing them are concerned.

RELATIONS OF SIDERITE-SLATE, FERRUGINOUS CHERT, AND ORE BODIES TO CLAY SLATES.

Owing to the scarcity of the outcrops of the sedimentaries in the Mansfield Valley, it is practically impossible to decipher the relations of the individual beds. Neither the study of the surface exposures nor the exposures in the mine workings have given definite results. That the beds represent interbedded strata is well understood, but the sequence of the strata is indeterminable. It is of especial interest to determine, so far as possible, the relations of the ferruginous rocks, in order that the possible iron-ore deposits associated with them may be found. A cross section through the Mansfield mine from east to west shows the following relations: The footwall of black hematitic slate is overlain by 25 to 30 feet of ferruginous chert and iron ore. This stratum is succeeded by "red slate," so called by the miners, which is probably weathered greenstone impregnated with iron. This is followed by a conglomerate, and this by amygdaloidal greenstone, of the overlying volcanic formation. The ore body extends north and south, agreeing thus with the strike of the slates. All drifts end on the north in mixed ore, and on the south in mixed ore, with "quartz-rock" and "lime-rock" of the miners in some places. From these facts we may justly conclude that the ore-bearing ferruginous cherts exist in beds in the slates or as lenticular masses which agree in dip and strike with the surrounding slates. This conclusion is confirmed by test pits along the strike of the exposed beds, which have disclosed similar ferruginous cherts at various places for a distance of half a mile to the north.

RELATIONS OF MANSFIELD SLATE TO ADJACENT FORMATIONS.

RELATIONS TO INTRUSIVES.

The Mansfield slates are surrounded on three sides—east, north, and south—by coarse-grained basic eruptive rocks. The fact that they are so surrounded by these rocks, which cut them off in the direction of their strike, points to the later origin of these eruptives. Moreover, the quartzitic character of some of the sedimentaries shows that they could not have been derived from the eruptives which stratigraphically underlie them, for in these no quartz is found. The quartzitic character would thus seem also to indicate that the slates are older than the intrusives. Wherever the

igneous rocks and slates are in contact or in close association, the latter have been metamorphosed, and adinoles, spilosites, and desmosites have been formed which are similar to those described as occurring in other areas along the contact zone of basic intrusives. Although no single instance of a dike penetrating the slates has been found, it can hardly be doubted from the relations which have been outlined that the slates are older than the intrusive dolerites.

RELATIONS TO VOLCANICS.

The sedimentaries are overlain by volcanics, both lava flows and tufaceous deposits. In these tuffs, at the northeast corner of sec. 7, T. 43 N., R. 31 W., angular black-slate fragments have been found similar in every respect to the slates of the Mansfield belt. From this it is clear that at least some of the volcanics are younger than part of the slate formation. In section 29 similar relations obtain, the only difference being that the masses of slate and graywacke are inclosed in rather larger fragments in a volcanic conglomerate, and still retain very closely their normal strike. In the conglomerates near the Mansfield mine are found chert fragments and in some places fragments of iron oxide. These latter were evidently not included as oxide, but as fragments of cherty carbonate. Like the great mass forming the ore body, the fragments have since their deposition been altered, forming iron-oxide bodies of small size. Further discussion of the relations between the volcanics and slates will be found under the heading "Hemlock formation."

STRUCTURE OF THE MANSFIELD AREA.

It has already been seen that the Mansfield rocks strike north and south and have a high westerly dip. The two possible explanations of this structure which are compatible with the facts in other portions of the area are (1) that they form a westward dipping monocline, and (2) that they are the western limb of an anticline.

THICKNESS.

As the sedimentaries forming the Mansfield belt now dip west at a very high angle, and as there is no evidence of duplication of strata due to folding, I feel comparatively safe in giving an estimate of their thickness. The belt is widest at the north end, and there has a breadth of about 1,950 feet.

The average dip of the beds is 80°, and this gives a maximum thickness of 1,900 feet. Toward the south the belt rapidly narrows, until it is cut out by the intruding dolerites. A thickness of 1,500 feet is probably not far from the average.

To the east of the Mansfield slates is a belt, varying in width up to about 1,200 feet, in which are found large masses of metamorphosed slates, surrounded by intrusive dolerite. In this belt the slate masses still show a general north-south strike, with slight variations to the east or west, and a westward dip. One might, perhaps, consider this a slate area which has been completely saturated with intrusives. If it should be so considered, this thickness should be added to the estimated thickness of the slates as above given, but as intrusives predominate in it, the slate being, as it were, merely incidental, I have preferred not to include it in the belt with the slate.

ORE DEPOSITS.

Although a great deal of exploring for iron ore has been done in the Mansfield slates, only one large body of ore has thus far been discovered, in which is the Mansfield mine. This mine is situated on the west bank of the Michigamme River, in secs. 17 and 20, T. 43 N., R. 31 W. The mine was apparently prospering when, on the night of September 28, 1893, a cave-in occurred, letting in the waters of the Michigamme River and drowning 28 miners.

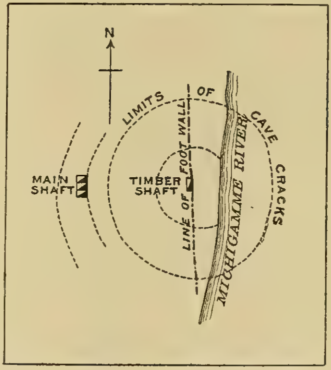


FIG. 6.—Concentric cracks formed by the caving in of the Mansfield mine.

For two hours after the caving occurred, the bed of the river below the mine was bare, the water flowing into the mine workings. The accompanying figure, fig. 6, prepared by J. Parke Channing, October 8, 1893, shows the relative position of the shaft and the river, and the concentric cracks caused by the caving of the mine. (Plan copied from address of president: Proc. Lake Superior Inst. Min. Eng., Vol. III, 1895, plate opposite p. 42.) The timber shaft is near the center of these cracks.

After the caving the mine remained idle until recently. At the present writing the DeSoto Mining Company has obtained control of the mine and, I understand, have freed it from water.

In May they began the task of diverting the channel of the river to a point several hundred feet south of the old course. They have dredged out a cut 2,650 feet in length by 100 feet wide and 18 feet deep. At the upper end of the new channel a cofferdam containing 14,000 cubic yards of earth has been constructed, and where the waters join the old outlet several hundred feet below the mine another embankment has been constructed across the course of the old bed that has 8,000 cubic yards of earth. This task was a very expensive one, and it has been well completed, the old channel being perfectly dry.

The turning of the river's course brings out with startling distinctness the criminal negligence or carelessness of those who were working the mine at the time of the accident. The upper tier of timbers in the mine are plainly seen, as also the ground that had been cut out to receive the set that was being gotten into place when the waters broke through. This shows the miners had worked up to within 12 feet of the water of the river. A great crack in the formation shows where the water first gained entrance. The ore made up the bed of the stream—was a portion of the bed in fact—and the walls of the mine were nearly vertical. The ore deposit had a width of about 20 feet. The water pressure must have been considerable, and the blasting of the ore (as it is hard, and explosives are needed to loosen it) shattered the thin protection over the miners, permitting the water to find ready and unimpeded entrance into the mine. An engineer could not have been employed and the wildest sort of guessing must have been done by those who had the work in charge. No sane man would have permitted the opening of the deposit so near the river's bottom.[1]

Owing to the long abandonment of the mine, the direct sources of information have been closed. For a description of the ore body I am compelled to rely on such data as are available from existing notes and plats. I am especially indebted to a manuscript description of the mine by J. Parke Channing, and to Mr. C. T. Roberts, of Crystal Falls, for plats of the mine. The sketch of the mine here introduced, Pl. IX, is compiled from an original drawing of J. Parke Channing, reproduced on the plate cited, and from data obtained from other sources.

GENERAL DESCRIPTION OF MANSFIELD MINE DEPOSIT.

The Mansfield mine has an ore body varying from 16 to 32 feet in width. It is in almost vertical position; it has well-defined foot and hanging walls composed of impervious rock; it has a somewhat indefinite longitudinal extent. The ore is Bessemer and occurs in an iron-bearing formation, which corresponds in every particular to those of the other iron-bearing

[1] Report of Commissioner of Mineral Statistics of Michigan, George A. Newett, for 1896, p. 84.

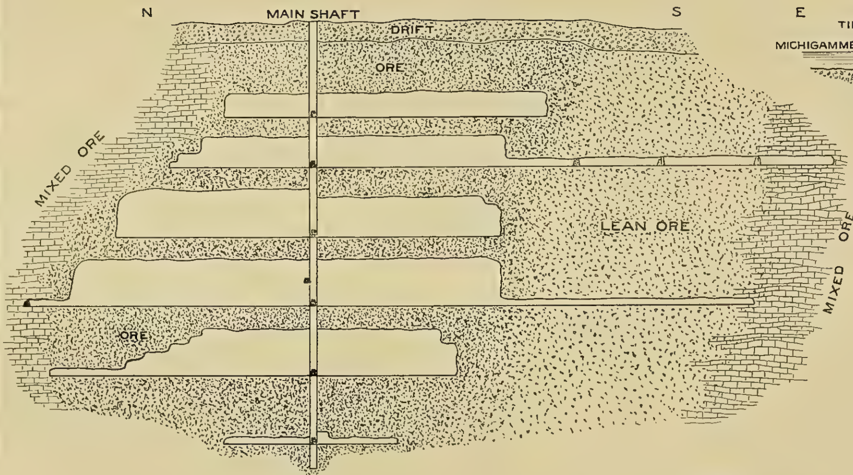
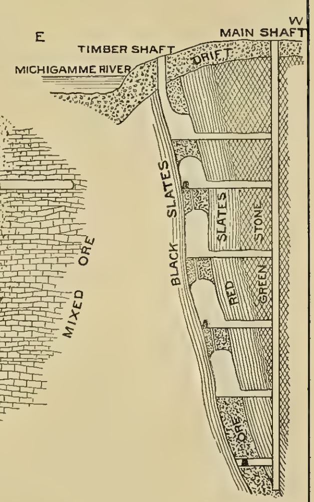


Fig. I



SCALE
0 100 200 FT

Fig. 2

SKETCH OF THE MANSFIELD MINE AS IT WAS BEFORE IT CAVED IN, IN 1893.

Fig. 1. Longitudinal section. Fig 2. Cross section.

districts of the Lake Superior region. The ore was first found in a test pit which passed through 9 feet of drift. The main working shaft was then located about 100 feet west of this point. It was put down to a depth of 460 feet before ore was struck. From this shaft crosscuts were driven east at average intervals of 70 feet, and the ore body was met at a distance varying from 74 feet at the first level to 10 feet at the sixth level. The crosscuts, in every case after leaving the greenstone, pass through so-called red slate, at the maximum about 25 feet thick, before ore is reached, this rock constituting the hanging wall. From these data the dip of the ore body may be calculated to be about 80° W., agreeing well with the observed dip of the slates, which outcrop over the area. The thickness of the ore, as shown by the cross sections, averages about 25 feet. The extreme variation in thickness ranges from two sets, or 16 feet, to four sets, or 32 feet. The strike of the slates is north and south, and the trend of the ore body agrees with this. This brings its southern end under the original course of the Michigamme River as the stream bends slightly to the west, south of the shaft. An examination of the longitudinal (north-south) section through the ore body does not determine whether or not it has a pitch. The southern boundary is nearly vertical from top to bottom, while the northern boundary lengthens about 140 feet between the first and the fifth levels.

In the northern end of the mine—that is, in line with the strike of the sedimentaries—the ore body terminates, in a more or less irregular way, in so-called mixed ore. This mixed ore continues to the north for over half a mile, as shown by the numerous test pits which have been bottomed in it. To the south of the mine shaft the ore body proper extends for 200 feet. It then changes its character, becoming a lean non-Bessemer ore. A long drift (335 feet) at the second level was run through this ore, and after leaving it penetrated a mixed ore, the so-called lime rock (siderite?) and quartz rock (chert?) of the miners. Three crosscuts along this drift show the ore body to vary from 20 to 30 feet in thickness, with the same foot and hanging wall as for the remainder of the mine. The same condition exists also lower down, as shown by a drift from the fourth level, 260 feet south. The figures on Pl. IX, giving longitudinal and cross sections of the mine, show clearly the dimensions of the ore body.

RELATIONS TO SURROUNDING BEDS.

The foot wall of the ore is a black slate, described as being rich in hematite and bearing large crystals of iron pyrite. No crosscuts have been driven for any distance into the foot wall, so that it is impossible to say what thickness of the hematitic black slate there may be before the greenish pyritiferous slate begins. In places a gray "soapstone" takes the place of the black slate as the foot wall.

The dump obtained by sinking the shaft in the material overlying the ore shows large masses of conglomerate, the pebbles of which are rounded and predominantly of volcanic rocks, with pebbles of chert and slate from the iron formation and slates below. These fragments are well rounded. The microscope also shows quartz grains with secondary enlargements, so that there can be no doubt that the rock is a true conglomerate. Similar conglomerates, except that the sedimentary fragments are wanting, have been noticed farther north along the west side of the river. Just west of the bridge at Mansfield, near the mine, there is also a small exposure of conglomerate, which shows an alternation of coarse and fine sediments, with a strike nearly north and south, and a dip of 80° W. To the west, above this conglomerate, and not more than 15 to 20 feet distant, are found the lavas of the Hemlock volcanics. According to the mine captain, the succession west from the ore body in the hanging wall is 20 to 25 feet of paint rock, or, as it is usually called, red slate, then conglomerate, then greenstone. It is difficult to diagnose the paint rock, as no specimens are to be had, but it is highly probable that it is a ferruginous and extremely altered lava sheet. Similar rocks are commonly found thus altered in association with the ores in the Penokee-Gogebic and Marquette districts. Lending weight to this conclusion is the fact that in some places an amygdaloidal greenstone has been exposed in test pits immediately above the iron-bearing formation.

COMPOSITION OF ORE.

The Mansfield mine up to the present time has raised only Bessemer ore, and is the only mine in the Crystal Falls district which has supplied any considerable quantity of ore of this character. An average of a number of analyses gives the following composition for the Bessemer ore:

Metallic iron, 64.80; phosphorus, 0.037; silica, 3.70.[1] According to Dr. N. P. Hulst,[2] those ore deposits in the Menominee range which have poorly defined walls carry a minimum of phosphorus. This body, however, shows that the same conditions do not exist at the Mansfield mine, since, while it has both sharply defined foot and hanging walls, it contains but a low per cent of phosphorus. From an examination of the analyses from which the above average was obtained I find that the percentage of phosphorus shows a marked increase in the lower levels of the mines over that of the higher, and there is also a slight corresponding decrease in the content of metallic iron. Increase of phosphorus with depth is also found in the adjoining Menominee range, as noted by Messrs. E. F. Brown,[3] of the Pewabic mine, and Per Larsson,[4] of the Aragon. It is impossible to state whether or not this distribution is due to the action of percolating water, as suggested by Hulst,[5] Larsson,[6] and other Michigan mining engineers. Only a large number of good analyses from carefully selected ores and associated rocks and a detailed study of conditions of occurrence could lead to any accurate determination of the reason for such distribution, and a discussion of these reasons is by no means warranted by the few and imperfect analyses of the Mansfield ores, which I have been able to obtain. The ore body changes in composition to the south of the shaft, as shown by the drifts in this direction. The ore in this part of the mine contains more phosphorus, alumina, and calcium, and less iron. This low-grade lean ore then passes over into the banded chert and ore mixed with the lime and quartz rock mentioned above.

MICROSCOPICAL CHARACTER OF THE ORES AND ASSOCIATED CHERT BANDS.

The ore varies from a soft limonitic hematite to a moderately hard hematite. It is for the most part opaque under the microscope, but in places shows bright-red to brownish-red color in transmitted light. In incident light the ore for the most part shows a dull-brown or reddish color, though in places it has a bright metallic reflection. In places in the ore

[1] An average of 62 per cent metallic iron and .030 per cent phosphorus is reported in Report of Commissioner of Mineral Statistics of Michigan (G. A. Newett) for 1896, p. 85.

[2] The geology of that portion of the Menominee range east of the Menominee River, by N. P. Hulst: Proc. Lake Superior Inst. Min. Eng., Vol. I, 1893, p. 28.

[3] Distribution of phosphorus and system of sampling at the Pewabic mine, Iron Mountain, by E. F. Brown: Proc. Lake Superior Inst. Min. Eng., Vol. III, 1895, p. 49.

[4] Op. cit., p. 52. [5] Op. cit., p. 28. [6] Op. cit., p. 53.

are spots, in which is a large quantity of chert mixed with iron oxide. As such ferruginous-chert areas increase in quantity the ore grades into the ferruginous chert and chert which is found associated with it in bands and lenticular areas.

ORIGIN OF THE ORE DEPOSITS.

The mode of occurrence and general characters of the ore body having been described, we are now prepared to determine the cause of concentration of the iron at this particular point and the source. From the description it was seen that the appearance of the body of ore was that of a bedded deposit. The microscopical examination shows, however, that the ore presents no evidences of clastic origin. An examination of the cherts and rocks of the area which are interbedded with the ore, and also a study of the southern contact of the ore body, shows that the ore is a chemical deposit, or the result of a replacement process, by which the original rock was largely removed, and its place taken by the present ore. It has been shown (p. 62) that the siderite bands pass into hematitic and limonitic chert bands. It has been seen that in the southern end of the mine the lean ore merges into a mass of ore bedded with chert and mixed with a rock called by the miners lime and quartz rock. I interpret this rock to be banded siderite and chert, possibly with some quartzite bands, all of which are found outcropping at the surface. The siderite evidently has been changed into iron oxide and the silica replaced by iron oxide, the banding of the original rock not having been destroyed thereby. Irving[1] considered siderite to be the source of similar ore and associated chert and jasper. Van Hise[2] has fully explained the process of the concentration of the ores of the Penokee-Gogebic and Marquette districts, and has applied the explanation to the other districts

[1] Origin of the ferruginous schists and iron ores of the Lake Superior region, by R. D. Irving: Am. Jour. Sci., 3d series, Vol. XXXII, 1886, pp. 255–272.

[2] The iron ore of the Marquette district of Michigan, by C. R. Van Hise: Am. Jour. Sci., 3d series, Vol. XLIII, 1892, pp. 116–132.

Iron ores of the Penokee-Gogebic series of Michigan and Wisconsin, by C. R. Van Hise: Am. Jour. Sci., 3d series, Vol. XXXVII, 1889, pp. 32–48.

The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise, Tenth Ann. Rept. U. S. Geol. Survey, Part I, 1890, pp. 341–507.

The Penokee-Gogebic iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey, Vol. XIX, 1892, pp. 245–290.

The Marquette iron-bearing district of Michigan, by C. R. Van Hise and W. S. Bayley, with a chapter on the Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey, Vol. XXVIII, 1897, pp. 400–405.

in the Lake Superior region. I shall not do more, therefore, than to add that the investigations in this area have shown the probable correctness of this explanation.

It is very interesting from an historical standpoint to note that as far back as 1868 Credner had made the suggestion, with reference especially to the Marquette district, that the ores were derived from an original iron carbonate. The following quotation will show his idea of the processes of development of the ore:[1]

> Sphaerosiderit wurde aus kohlensäurereichen Gewässen abgesetzt, durch eine theilweise Oxydation desselben entstand Magneteisenstein, durch weitere Aufnahme von Sauerstoff das Gemenge von Magneteisenstein und Rotheisenstein und endlich reiner Rotheisenstein; aus diesem sporadisch durch Zutritt von Wasser Brauneisenstein.

Credner's suggestion seems to have been lightly considered by other workers in that area. In 1886 Irving[2] suggested the theory of replacement of an original ferruginous carbonate to explain the Penokee-Gogebic iron ores. This theory has since then been elaborated by Van Hise, and shown to have a wider application to the other Lake Superior ore districts. He has also traced the iron to its source in the rocks removed by denudation, and shows why it occurs in the positions in which the ore bodies are at present found to occur. Moreover, Van Hise has also explained the process of development in detail, and, what is perhaps far more important, the reason certain ores develop and not others. In its essentials, however, the process is the same as that suggested by Credner in the lines quoted above, though in them no suggestion of the replacement to which is due the enrichment of the ore bodies is made.

Much of the iron of the Mansfield ore is presumed to have resulted directly from the alteration of the ferruginous carbonate in place, but a large amount was brought in from above by infiltrating waters. The ferruginous matter, which was taken into solution during the denudation of the area, has been carried down by percolating waters and deposited at places favorable for its accumulation. The beds are now on edge, offering the most favorable condition to percolation. The conclusion is obvious that these deposits

[1] Die vorsilurischen Gebilde der "Oberen Halbinsel von Michigan" in Nord-Amerika, by H. Credner: Zeitschr. deutsch. geol. Gesell., Vol. XXI, 1869, p. 547.

[2] On the origin of the ferruginous schists and iron ores of the Lake Superior region, by R. D. Irving: Am. Jour. Sci., Vol. XXXII, 1886, p. 263.

were formed after the beds were tilted, and the iron derived from the upward extension of the rocks, which has been removed by erosion.

CONDITIONS FAVORABLE FOR ORE CONCENTRATION.

The conditions favorable for the accumulation of ore deposits have been ascertained by Van Hise from studies in the other iron-bearing districts of the Lake Superior region. He summarizes these results as follows:[1]

[1] The iron ore is confined to certain definite horizons, known as the iron-bearing formations. . . . [*a*] All ore bodies have been found to be distributed very irregularly in these iron-bearing formations. This is due to the fact that they are secondary concentrations produced by downward percolating waters, and the ore bodies therefore occur at the places where water is concentrated, in accordance with the laws of the underground circulation of waters. [*b*] These places are just above an impervious formation, at the contact of the Upper Huronian and Lower Huronian and where the rocks are shattered. [*c*] The impervious basement formation may be a surface volcanic, a subsequent intrusive, an argillaceous stratum, or any other impermeable formation. [*d*] These impervious basements are most effective when they are in the form of pitching troughs, thus concentrating the waters from the sides along a well-defined channel. These pitching troughs may be formed by a single one of the above rocks or by a combination of two or more of them. The horizon marked by the unconformity between the Upper and Lower Huronian is a great natural zone of percolating waters. Here oftentimes the basement formation of the Upper Huronian is itself a lean ore, having derived its material from the Lower Huronian, but in this case a secondary concentration has occurred in order to produce the present ore bodies. [*e*] Finally, as a result of folding, the iron-bearing formations have been shattered, thus producing natural water-courses. More frequently than not, more than one of these classes of phenomena are found together where the great ore bodies occur, and in many cases all are combined. The original source of the iron ores has been ascertained to be in many cases a lean carbonate of iron, often with a good deal of carbonate of calcium and magnesium, formed as an ocean deposit.

Van Hise adds to the above statement that generally the ore bodies, as a result of their methods of concentration, somewhere reach the rock surface.

The Mansfield ore body has well-defined foot and hanging walls of normally impervious rock. The iron-bearing formation is much fractured. We thus have certain of the conditions favorable to the concentration of an ore body. Whether a trough is completed by a slight cross fold in the formation, or possibly by an intersecting dolerite dike, has not been determined.

[1] Fourteenth Ann. Rept. U. S. Geol. Survey, Part I, 1893, pp. 107-108.

EXPLORATION.

Exploration has developed no other deposits along the Mansfield slate belt.[1] If other deposits exist, it is highly probable that they extend to the rock surface—that is, are covered by the drift mantle alone.

The intervals between possible ore bodies along the strike of the slates are probably occupied by mixed chert and ore or ferruginous chert. Explorations should extend from the impervious slate below the iron-bearing formation to the impervious rock above the iron-bearing formation. In order to explore the belt thoroughly, rows of pits cross-sectioning the formation ought to be made at intervals not greater than 100 feet, and even with such intervals an important deposit might be missed, for it frequently happens that at the surface of the rock an ore deposit is smaller than it is at a moderate depth.

SECTION III.—THE HEMLOCK FORMATION.

This formation, the most interesting petrographically in the Crystal Falls district, consists almost exclusively of typical volcanic rocks, both basic and acid, with crystalline schists derived from them. Sedimentary rocks play a very unimportant rôle. With one exception they have been formed directly from the volcanics, and occur interbedded with them. Cutting through the volcanics are intrusive rocks, which likewise include both basic and acid kinds. Chemically the intrusive and extrusive rocks show very close relationships. The name Hemlock has been given to this volcanic formation because the river of that name flows through it for a number of miles, and in places affords excellent exposures.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Beginning in sec. 36, T. 46 N., R. 32 W., the place where the Hemlock formation enters the part of the district studied by me, the formation has a width of one-half of a mile. From this place the formation has a northwestern course for about 5 miles, gradually widening. It then bends to the west, and after a short distance to the south, which course it follows for about 9 miles. In township 45 N., Rs. 32 and 33 W., the belt has a maximum width of 5 miles. At the end of the southern course the formation

[1] Since the above was written I have been informed that Mr. George J. Maas, of Negaunee, has, with a diamond drill, located a body of bessemer ore 30 feet thick on lot 6, sec. 20, T. 43 N., R. 31 W., 1 mile south of the Mansfield mine.

bends to the southeast, and continues with this general trend for about 16 miles into T. 42 N., R. 31 W., where my field study of it ended. At the north the belt runs into the eastern half of the district described by Smyth, and swings south, which course is followed for some 15 miles. The entire belt thus forms an oval surrounding the sedimentaries, except in the southeastern part of the district. Another area of Hemlock volcanics is found in T. 43, Rs. 32 and 33, just north of Crystal Falls. This area is about one-half a mile wide just north of the city of Crystal Falls, but rapidly widens as it is followed to the west until at the western limits of the area it is about 3½ miles wide. A third small isolated area is found in secs. 17, 18, 19, and 20, T. 42 N , R. 32 W., and sec. 24, T. 42 N., R. 33 W., about 4 miles south of Crystal Falls.

The topography of the Hemlock formation is exceedingly rough whereever erosion has succeeded in cutting through the drift mantle. This occurs only adjacent to some of the streams. The rough topography at these places is due to differential erosion working upon rocks approximately on edge, and of varying hardness. The valleys usually indicate the location of beds of tuff and the higher grounds are almost universally occupied by dense rocks forming the lava flows, or of the coarse-grained massive intrusive rocks. In a few places, however, the thoroughly consolidated and indurated tuffs form high hills. In traversing the Hemlock formation one makes an abrupt ascent, followed by a sharp descent into a narrow swamp, then another ascent, and so on. Exposures appear for the most part in small areas along the edges of the swamps and scattered over the faces of the hills. These are fairly numerous, but so small and disconnected as to prevent the tracing out of the individual flows, although this might be possible if the traverses were made at very short intervals and the area mapped in great detail.

THICKNESS.

As has been seen, the belt of eruptives varies in width from one-half of a mile to nearly five miles. The dip of the rocks is about 75° W. The enormous thickness of 25,500 feet which these data would give is probably illusory.

In the case of the assumption of the thickness of a series of lava flows and tuffs, it is important that the initial dip, which these deposits must have, be considered. This dip varies greatly, depending on the slope of the

cone, which in its turn, is dependent on the viscosity of the lava and the presence of varying quantities of fragmental products. If we assume these pre-Cambrian volcanic products to have had an initial dip of 15°, I believe we are within limits for products consisting, as these do, of what was probably moderately viscous basalt and vast masses of fragmental material. This estimate is based on the assumption that the volcanics here represented were deposited for the most part upon the westward slope of a volcano, or a series of volcanoes. This initial dip of 15° is then to be deducted from the present dip, 75°, of the flows. Taking this into consideration, we get a thickness of 23,000 feet for the volcanics.

It is highly probable that the rocks have been subjected to close folding, and for this reason also the apparent thickness would be much greater than the true thickness. The schistose character of some of the rocks shows clearly that they have been severely mashed, and this mashing was probably produced in connection with folding. It is probable that this possible maximum thickness should be very materially reduced, possibly to one-half or one-third of the amount. However, even the maximum above calculated is probably paralleled by the vast masses of volcanic material accumulated in certain volcanic areas, such as those of Hawaii or Iceland. Geikie writes:[1]

> The bottom of these Iceland Tertiary basalts is everywhere concealed under the sea. Yet their visible portion shows them to be probably more than 3,000 meters in thickness.
>
> An especial interest belongs to this Icelandic plateau because volcanic action is still vigorous upon it at the present day.

RELATIONS TO ADJACENT FORMATIONS.

In the northern part of the Crystal Falls district the volcanics overlie the quartzose dolomite formation known as the Randville dolomite. In the central part of the district, through which the Deer River runs, as shown in section *G–H*, Pl. VI, outcrops are so scarce that it has been found impossible to trace the boundaries of the formations with any degree of accuracy. Consequently this part of the district is mapped as Pleistocene.

From the few outcrops of slate, probably equivalent to the Mansfield slate, which have been found in the Deer River area, it has been thought

[1] The Tertiary basalt-plateaux of northwestern Europe, by Sir A. Geikie; Quart. Jour. Geol. Soc. London, Vol. LII, 1896, p. 395.

highly probable that this slate in an extremely plicated condition may underlie the volcanics of this area, and it is so represented in section *G–H*, Plate VI. As evidence of this, in T. 43 N., R. 31 W. the volcanics overlie the Mansfield slate unconformably.

In places test pits have disclosed an amygdaloidal lava flow immediately overlying the Mansfield slates. At one place, at the northeast corner of sec. 7, T. 43 N., R. 31 W., angular fragments of the underlying black slate have been found in the tufaceous deposits of the Hemlock volcanics. Farther south, along the contact just west of the Mansfield mine, a conglomerate is exposed, which contains fragments of slate, lava, and rounded grains of quartz with secondary enlargements. The rock is evidently water deposited. There is also obtained from the workings of the mine a conglomerate, taken from just above the ore, which consists of lava fragments and pieces of chert and ore, as mentioned on pp. 64, 68. From these occurrences it is clear that some of the sedimentaries are unquestionably older than some of the volcanics, and yet the conglomerates bearing the fragments of ore and slate contain also fragments of lava, showing the existence of some of the volcanics before the deposition of this conglomerate. The only explanation of all of the facts which has occurred to me is as follows: After the ore-bearing Mansfield slate was deposited, an erosion interval occurred. Then followed a volcanic outbreak. It is highly probable that this outburst began far north of the Mansfield mine, coincident with the upheaval which resulted in the erosion of the Mansfield slate. The volcanic ejectamenta were mixed with the sedimentary fragments and all together were rounded and bedded, forming in places conglomerates. In places along the shore lava flows descended, some reaching into the sea and covering the sedimentaries along the shore where no conglomerate had been formed. At other places deposits of scoriæ, etc., including fragments of slates from the sedimentaries through which the volcano burst, were made, and thus deposits of tuff are found overlying the sedimentaries. The various deposits, though really separated by a slight physical break, are practically conformable with the series below, all having a north-south strike and a high westward dip.

The formations which underlie the volcanics in the northern and southern parts of the district are of different character. This difference

may be explained by supposing the volcanoes broke out in the northern part, while the Mansfield slate was still being deposited in the south. Gradually, however, the volcanic activity spread toward the south, probably following a fissure along the pre-Cambrian shore, and igneous materials buried the Mansfield slate. Hence, while on the whole these volcanics are younger than the Mansfield slates, some of the lower of them are contemporaneous with some of the upper Mansfield beds. The volcanics invariably overlie the Randville dolomite, and are unquestionably of later age than that formation.

The Hemlock volcanics are overlain throughout their extent by the Upper Huronian series of graywackes and slates. Near the contact line with the volcanics wherever the Huronian outcrops, or has been exposed by exploration, it has been found to be characterized by a line of magnetic attraction. By means of magnetic observations the line of contact has been traced, where owing to lack of exposures it would have been otherwise impossible to connect the isolated outcrops.

RELATIONS TO INTRUSIVES.

High ridges composed of dolerite are found extending in a general northwest and southeast direction through the volcanics. That these masses were forced up through the Hemlock formation is indicated by the folding which they cause in certain places. Such rocks are unquestionably younger than the volcanic series. There may be seen also on the map, in T. 44 N., R. 32 W., a number of isolated knobs. These are also doleritic, and are presumed to be, like the larger ridges, intrusive in the volcanics.

The dolerites have in their turn been cut by acid dikes. These are coarse micropegmatitic granites. Similar acid dikes have been found cutting the surrounding volcanics. This set of acid dikes may be looked upon as the youngest intrusive igneous rocks occurring in the Hemlock volcanic formation.

Cutting the volcanics are also basic dikes varying from fine to moderately coarse grain. It is well known that during a volcanic epoch the outpoured lavas and clastic volcanic deposits are penetrated by dikes coming from the same magma. Whether or not these dikes are of this origin, and are hence contemporaneous with the later volcanics, or are of later age, and

correspond to the coarse dolerites, it is impossible to determine with certainty. They are presumed, however, to form an integral part of the Hemlock volcanics, as no connection between the dikes and the unquestionably intrusive dolerites could be traced in the field.

VOLCANIC ORIGIN.

In spite of numerous occurrences of ancient volcanics which have recently become known, the late Professor Dana makes the following statement:[1]

> It is not yet certain that a volcano ever existed on the continent of North America before the Cretaceous period; for the published facts relating to supposed or alleged *volcanic* eruptions in the course of the Paleozoic ages are as well explained on the supposition of outflows from fissures and tufa ejections under submarine conditions; and none of the accounts present evidence of the former existence of a volcanic cone, that is, of an elevation pericentric in structure made of igneous ejections.

The presence in the Hemlock formation of a quantity of pyroclastics, great in proportion to the solid lavas, and the absence of any great sheets of lava, so important a product of great fissure eruptions, seem to point to the derivation of the Hemlock rocks from a volcano or volcanoes situated near the border of the contemporaneous Huronian sea, rather than from a simple fissure. While some of the eruptives may have been submarine, the occurrence of large quantities of clearly subaerial deposits shows that the eruptives were largely on the land. Thus it appears that neither a fissure flow nor a submarine volcano will wholly explain the Hemlock formation. However, it is highly probable that this volcanic outburst, which piled masses of volcanic material upon the land, was accompanied, as have been all or nearly all the great outbursts of recent times, by submarine lava flows and tuff ejections. No such clear evidence of the presence of a Paleozoic or pre-Paleozoic volcano on the North American continent has been adduced as that given by the English geologists for certain volcanoes in the British Isles. But while the presence of a central cone with pericentric arrangement in the Hemlock district is not conclusively proven, the presumption in favor of such a cone or cones having existed is certainly strong.

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[1] Manual of Geology, by J. D. Dana: 4th ed., 1895, p. 938.

An attempt was made to locate the vent or vents from which the material was derived, but no evidence could be found, unless we consider the vents to have been where the accumulations were the greatest. The coarse-grained rocks which were first supposed to represent the plugs of ancient volcanoes, on careful and detailed examination appear to be later intrusives, or else are indeterminate.

CLASSIFICATION.

The general character and distribution of the Hemlock formation having been given, we may now proceed to a petrographical consideration of the rocks comprising it. This will be given in more detail than for the other rocks of the Michigamme district because this great pre-Cambrian volcanic formation possesses peculiar interest.

The rocks of the Hemlock formation are chiefly of direct igneous origin. Some interleaved sedimentary rocks occur, which, however, with a single exception are composed of fragments of the igneous rocks. For the sake of easy reference, the usual classification into igneous and sedimentary rocks will be used. The massive igneous rocks are subdivided according to chemical composition into acid and basic rocks. The acid rocks include rhyolite-porphyries,[1] aporhyolite-porphyries, and acid pyroclastics. The basic rocks include altered nonporphyritic basalts, porphyritic basalts, and variolite and basic pyroclastics. The sedimentary rocks are divided into the volcanic sedimentaries and the nonvolcanic sedimentaries or normal sedimentaries. The first include tuffs and ash beds—the æolian deposits, and volcanic conglomerates—subaqueous deposits. The normal sedimentaries are represented by slates and limestones. Various schists are locally produced from these numerous kinds of rocks through metasomatic changes and dynamo-metamorphic action. Many of these schists resemble one another very closely, though, as will be seen later, they are derived from both the massive rocks and from the clastics. These have been described in connection with the rocks from which they have been derived.

[1] According to a late ruling of the Director of the United States Geological Survey, based on the recommendation of a committee on nomenclature for geologic folios, "porphyry" is to be used only with a textural significance. Hence "quartz-porphyry," according to this ruling should no longer be used as a rock name. The rhyolite-porphyries here described are what have been known as normal quartz-porphyries.

The following table will show the arrangement outlined above, which will be followed in the descriptions:

Classification of the rocks of the Hemlock formation.

Igneous	Acid	Lavas	Rhyolite-porphyry	Schistose acid lavas	Crystalline schists.
			Aporhyolite-porphyry		
		Pyroclastics			
	Basic	Lavas	Metabasalt	Nonporphyritic	
				Porphyritic	
				Variolitic	
		Pyroclastics	Eruptive breccia	Eruptive breccia	
				Flow breccia	
Sedimentary	Volcanic sediments	Eolian deposits		Tuffs	
				Ash beds	
		Subaqueous deposits		Conglomerates	
	Normal sediments	Slate			
		Limestone			

ACID VOLCANICS.

The acid volcanics are comparatively unimportant in quantity. They may be conveniently subdivided into the lavas and pyroclastics.

ACID LAVAS.

The acid lavas occur in such small quantity as to make it impossible without very great exaggeration to place them upon the accompanying small-scale general maps, though they have been introduced upon the detail maps wherever the scale permitted. They usually form isolated ridges, and their relations to the surrounding basic volcanics are obscured by lack of exposures. The trend of the individual ridges agrees with the general strike of the banding in the basic tuffs. Moreover, in nearly all cases the isolated exposures which are closest together lie in such relations to one another that when connected the large sheets thus formed follow the strike of the tuff banding, as do the individual ridges, and they are therefore confidently assumed to be the isolated portions of acid flows interbedded with the basic volcanic rocks.

The rock types represented are the two closely related rocks—the rhyolite-porphyry and the aporhyolite-porphyry. Under the rhyolite-porphyries are included the porphyritic acid lavas, which have, so far as can be determined, an original holocrystalline groundmass. Under the aporhyolite-porphyry, following Miss Bascom's use of *apo*,[1] I include those

[1] Structures, origin, and nomenclature of the acid volcanic rocks of South Mountain, Pennsylvania, by Miss Florence Bascom: Jour. Geol., Vol. I, 1893, p. 816.

acid lavas which are now likewise holocrystalline, but which owe this character to the devitrification of an original glassy base, supposing them in their original vitreous condition to have corresponded to the modern hyalorhyolite-porphyries.

RHYOLITE-PORPHYRY.

The rhyolite-porphyries on fresh fracture are dark grayish-blue to black. From this they grade with advancing alterations through chocolate brown to purplish. The weathered surface varies from white to reddish. The weathering has in one case brought out very well the fluxion banding of the rock. Their texture is very pronouncedly porphyritic. The quartz and feldspar crystals stand out plainly from the groundmass, which is usually dense with a somewhat resinous luster. The porphyritic quartzes average perhaps the size of a small pea, and hence are macroscopically very plainly visible. They frequently stand out on the weathered surface and show their crystal forms, and in other cases we see the angular cavities out of which they have fallen, like the kernel from the nut.

Under the microscope the rocks are seen to be typical rhyolite-porphyries. The phenocrysts are chiefly corroded dihexahedral crystals of quartz. Crystals of plagioclase and orthoclase are less common. These lie in a very fine-grained holocrystalline groundmass, composed largely of feldspar and quartz, with some zircon in small crystals, and here and there magnetite.

These are presumed to be the original constituents of the groundmass. Associated with them are considerable quantities of secondary chlorite, epidote, biotite, muscovite, calcite, and reddish to brown alteration products of the magnetite. Included in the groundmass are here and there oval areas of finely crystalline secondary quartz, probably filling former amygdaloidal cavities.

In thin section the crystal contours of the quartz phenocrysts are more or less rounded, with here and there embayments of the groundmass projecting into them. The crystal form is, however, always clearly marked. In some cases the individuals have been broken before the cooling of the magma, the fragments of an individual, though now separated, being seen to conform to one another. That they have been subjected to pressure is shown by the undulatory extinction and also by the separation

of the black cross of uniaxial minerals into hyperbolæ. Embayments of groundmass, and liquid inclusions in which a dancing bubble may be seen, are in places rather thickly distributed through the quartz. The liquid inclusions have very commonly an hexagonal form, corresponding to the contours of the inclosing quartz.

These liquid inclusions are certainly in some cases secondary. This character is well shown in some of the crystals, which are broken across, giving along the line of fracture a very wavy extinction. Along this line of fracture the greatest quantity of inclusions are seen, both with and without bubbles. As the distance from a fracture increases, both the undulatory extinction and the number of inclusions diminish. (See fig. *A*, Pl. XIX.) These fractures in the quartzes are but continuations of those which extend in many cases all the way across the section. The fractures have since been healed by secondary quartz. This secondary quartz has also in some cases healed the fractured quartz phenocrysts, and then agrees with them in orientation. The possession of an imperfect rhombohedral parting is very noticeable in a number of quartzes, and especially those which, being on the edge of the section, are very thin. (See fig. *B*, Pl. XIX.) Similar parting in the quartz occurs in various rocks studied in this district.

The phenocrysts of the porphyries are traversed by fractures, some of which are more or less circular, and simulate very imperfectly perlitic cracks. With the exception of those in porphyries in two localities, the quartz phenocrysts are surrounded by zones, largely of quartz, of varying widths, and considerably lighter than the remainder of the groundmass. Much of the quartz of these zones has the same optical orientation as the phenocrysts. In those sections in which the zones are observed they occur around every section of quartz.

The feldspar phenocrysts are orthoclase and plagioclase, the latter apparently predominating. They occur usually in rounded, badly corroded crystals, with indentations filled with groundmass. They are always altered, and have associated with them as secondary products calcite, epidote, muscovite, biotite, and chlorite

No large original ferro-magnesian phenocrysts appear to have been present in the porphyry. Their former presence is at least not indicated by any aggregates of secondary products. Whatever ferro-magnesian min-

erals were present must have been scattered through the groundmass, and have been completely altered. The secondary minerals contained in the groundmass are chlorite, calcite, epidote, muscovite, and biotite.

TEXTURE OF THE PORPHYRIES.

The texture of the dense groundmass varies according to the mode of association of the two chief minerals—quartz and feldspar. The commonest variety is the rhyolite-porphyry with microgranitic groundmass (porphyre granulitique of Michel Lévy). A second variety is the rhyolite-porphyry with micropoikilitic groundmass.[1] The microgranitic texture is too well known to warrant a description of it here.

The micropoikilitic texture presents certain characters which render a further description desirable. This peculiar phase of the micropoikilitic texture was briefly described by the writer and illustrated by microphotographs in 1895.[2] Shortly after the separates of this article were distributed, I received from H. Hedström, of the Swedish Geological Survey, an article published in 1894 containing a description of what appears to be very nearly the same texture.[3] If I have understood the description correctly, however, there seems to be one essential difference. In order to explain clearly this difference, I shall describe the texture in detail.

In certain of the rhyolite-porphyries, as already mentioned, the quartz phenocrysts are surrounded by certain zones. These zones in the rocks having a micropoikilitic texture possess exactly the same texture as does the groundmass. The zones are composed of minerals which are of sufficient size to permit readily their determination. Quartz and feldspar are the essential components, with some chlorite, epidote, muscovite, and iron oxide. The first two are the important minerals, and will alone be referred to in the further description. The chief peculiarity of the zone is in the arrangement of the two minerals, and this character is best shown on the accompanying microphotographs. This texture can be seen even in ordinary light. It is brought out better when the field is partly shaded, so

[1] Eruptive rocks of Electric Peak and Sepulchre Mountain, by J. P. Iddings: Twelfth Ann. Rept. U. S. Geol. Survey, 1891, p. 589. On the use of the terms poikilitic and micropoikilitic in petrography, by G. H. Williams: Jour. Geol., Vol. I, 1892, pp. 176–179.

[2] Volcanics of the Michigamme district of Michigan, by J. Morgan Clements: Jour. Geol., Vol. III, 1895, pp. 814–816, figs. 1 and 2.

[3] Studier öfver Bergarter från Morän vid Visby, by H. Hedström: Geol. Fören i Stockholm Förhandl, Bd. 16, H. 4, 1894, pp. 5–9.

as to exhibit the difference in relief of the minerals, and, best of all, between crossed nicols. (See fig. *A*, Pl. XX.) The zones are seen to be made up of reticulating areas of clear quartz, in which lie embedded irregular pieces of feldspar. Where two or more of the quartz stringers or needles unite, one sees broad areas of limpid quartz. The network of quartz is best seen when it exhibits its highest polarization color, as then the feldspar is for the most part dark. The pieces of feldspar in such a quartz area for the most part have irregular orientation, as is shown by their varying extinction, although a number extinguish simultaneously. This quartz net is connected with the quartz phenocrysts, as shown by the continuation of the quartz of the phenocrysts and that of the zone, and the consequent agreement in orientation. The lack of a uniform optical orientation of the feldspar grains is made especially apparent when the quartz is cut perpendicular to the *c* axis, and consequently remains dark under crossed nicols. Under the above circumstances we see certain feldspar grains polarizing in the zone around the quartz, and as the stage revolves other particles lighten as those which polarized in the previous position of the stage become dark. From this description it is evident that the texture is not micropegmatitic according to the generally accepted definition of the term, but corresponds to the micropoikilitic, as described by Iddings and Williams.[1]

A gradation toward a spherulitic texture was noticed in one instance where a number of long quartz stringers were arranged perpendicular to the periphery of the quartz phenocryst. (Fig. *B*, Pl. XX.) The texture of this micropoikilitic mass, it will be observed, is finer than that before described.

The groundmass of the porphyries is formed of irregular roundish areas having exactly the same micropoikilitic texture as the zones surrounding the quartz phenocrysts. An explanation of the origin of the zones should therefore also explain the texture of the groundmass. Certainly in many cases, probably in most cases, the groundmass areas result from tangential sections through one of the micropoikilitic zones surrounding the quartz phenocrysts.

The description given by Hedström[2] of this same structure as observed by him is essentially the same as the above, if I have understood him correctly. The following difference is, however, to be noted. In speaking of

[1] Op. cit., pp. 589 and 179.

[2] Op. cit., p. 8.

the structure where the quartz is surrounded by this micropoikilitic zone, he calls it the granophyric structure. As I have already emphasized above, the feldspars in the network of quartz have varying orientation, and the structure is, strictly speaking, micropoikilitic, and in no sense granophyric (micropegmatitic). Moreover, he describes in addition to the above type one in which are found phenocrysts of quartz lying in a micropoikilitic groundmass with the above reticulating texture, but the phenocrysts abut sharply against the groundmass, instead of being connected with it by means of these zones.

The micropoikilitic texture has been held in some cases to be of secondary origin and the result of devitrification. While recognizing that there may be certain unquestionable cases where a micropoikilitic structure results from the devitrification of a glassy groundmass, I can find no evidence in the rocks here described that points to this origin for the micropoikilitic texture under discussion. On the other hand, there is an absence of evidence that indicates its unquestionably primary character. Rather than to regard the quartz as secondary and influenced in its orientation by the phenocrysts, as in the enlargements of quartz grains, it seems natural to suppose that when the lava was extruded after the crystallization of the phenocrysts, there began, consequent upon the diminished pressure and temperature and other factors, a rapid crystallization of the mineral elements from the remaining magma. This resulted in the production of the feldspar in very imperfect and small crystal individuals. At the same time the quartz of the phenocrysts continued to grow, and in so doing inclosed these small feldspars in its meshes.

In certain rhyolite-porphyries the micropoikilitic texture is somewhat different from that above described. In these the quartz phenocrysts are surrounded by zones which are illustrated in figs. *A* and *B*, Pl. XXI. These appear to correspond very closely to the ones described by Michel Lévy[1] and Williams,[2] and since described by many other writers. The zones have a much higher index of refraction than the quartz of the phenocrysts, and hence contrast strongly with it. Examined closely, they are seen to be composed of chlorite, epidote, and black or reddish

[1]Annales des Mines, Vol. VIII, 1875, pp. 378, 381.

[2]Die Eruptivgesteine der Gegend von Triberg im Schwarzwald, by G. H. Williams: N. Jahrb. für Min., Bd. II, 1883, p. 605.

ferruginous grains, which lie in a white matrix. This matrix shows the following characters: The greater part of it extinguishes and lightens simultaneously with the quartz phenocrysts which it surrounds, and is consequently believed to be quartz. When the matrix and quartz phenocrysts are dark, one sees scattered through the matrix, making up a very small proportion of the total zone, certain irregular areas which show polarization effects. These are believed to be feldspar grains, though this could not be determined. With the highest magnification no radial arrangement of the quartz and feldspar could be observed which would warrant the inclusion of these aureoles under Michel Lévy's term "*sphérolites à quartz globulaire*."[1] Where two quartz crystals with different orientation are in juxtaposition, each possesses its own zone corresponding with it in orientation. The way in which the zones about the quartzes are confined to the quartz is clearly shown in one case in which a very much altered feldspar phenocryst was found, one portion possessing a typical coarse micropegmatitic texture. In this case where the quartz of the micropegmatitic intergrowth touches the groundmass, it grades into a micropoikilitic area, whereas the feldspar does not do so.

The texture of the zones about the quartzes is apparently but a fine-grained variety of the micropoikilitic texture, the coarser phases of which are illustrated on Pl. XX.

The groundmass of the rocks showing the texture is composed of roundish areas of exactly the same composition as the zones around the phenocrysts, with a feldspar of small dimensions here and there between these areas. (See fig. *B*, Pl. XXI.) The texture approaches very closely if it does not correspond exactly to the quartz épongeuse phase of the quartz-globulaire texture of the French.[2] In one part of a section of rhyolite-porphyry the quartz phenocrysts have aureoles and the groundmass has the texture just described. In another portion of the section the quartz phenocrysts have no aureoles and the groundmass possesses an imperfect micrographitic texture (structure microgranulitique of Michel Lévy). This shows the passage of a micropoikilitic textured rock into one with a micrographitic texture. I explain the aureoles and the roundish areas in the

[1] Structures et classification des roches éruptives, by A. Michel Lévy, Paris, 1889, p. 21.

[2] It is found to show exactly the same texture as seen in a section obtained from Paris and labeled "Porphyre à quartz globulaire de la Sarthe."

groundmass as original, in exactly the same way as has been suggested by Williams[1] for those which he described. This is essentially the same explanation which I have given on a previous page for the less common, coarse micropoikilitic phase. The cause of the formation of the micrographic phase appears, however, rather difficult to discern. Its development seems to depend upon peculiar local conditions.

APORHYOLITE-PORPHYRY.

Intimately associated with the rhyolite-porphyries are rocks very similar to them in mineral constituents, both macroscopically and microscopically, so that the description of the rhyolite-porphyries will largely answer for the aporhyolite-porphyries. Flow texture, however, is well shown by the aporhyolite-porphyries. A beautifully developed perlitic parting, fig. *A*, Pl. XXII, is taken to indicate the presence of an original glass; hence the rocks are classed with the aporhyolites. The perlitic cracks are well brought out in ordinary light by the chloritic flakes along them. Between crossed nicols these disappear, and the groundmass resolves itself into a fine-grained mosaic of quartz and feldspar. (Fig. *B*, Pl. XXII.) This groundmass has all the characters of that of a microgranite.

No evidence which would point to the devitrification of a glass could be seen other than the presence of a perlitic parting, as described. For recent excellent descriptions of similar devitrified lavas in which various structures characteristic of vitreous lavas have been identified, the reader is referred to the articles already mentioned, and the one by Dr. Bascom,[2] in which a moderately full bibliography is found.

SCHISTOSE ACID LAVAS.

The results of the ordinary alterations of the acid lavas, chiefly metasomatic in character, by which the phenocrysts and the matrix have been changed, have been briefly described. The results produced by dynamic action are more interesting and perhaps more striking. The mashing, resulting in chemical changes and schistose structure, has in many cases almost obliterated the porphyritic texture, and in extreme cases destroyed all internal evidence of igneous origin. Even the fluxion banding, as is well known, at times simulates very closely sedimentary bedding, and thus increases

[1] Op. cit., p. 607.

[2] Acid volcanic rocks of South Mountain, by Dr. Florence Bascom: Bull. U. S. Geol. Survey No. 136, 1896, p. 87.

the difficulty of determining the igneous character of the rock. In the rocks to be described the phenocrysts may still be observed, though more or less deformed, and the fluxion banding has been in one case exceptionally well preserved, so that no doubt is felt as to their igneous character. Dynamically metamorphosed rhyolite-porphyry flows have been found in two areas in the Hemlock formation. In the following each area will be described separately, the one in which the original character of the porphyry is least in doubt being considered first.

The Deer River schistose porphyries are found in the SE. $\frac{1}{4}$ sec. 36, T. 44 N., R. 32 W., beginning at 400 N., 250 W., and continuing to 600 N., 350 W., of the southeast corner near the bridge on the Floodwood road. They occur in several outcrops which are practically continuous, being separated by very short distances, and are so much alike both macroscopically and microscopically that there is sufficient reason for the conclusion that they belong together. Their field relations to other rocks have not been observed. No data have been found which offer any clue as to the time of eruption of these rocks other than the fact that they are surrounded by the basic volcanics of the Hemlock formation and have undergone the same dynamic action.

The porphyries are dense, bluish-black rocks, with porphyritic crystals of red feldspar. A fluidal structure is not present in them. The schistose structure is apparent to the eye, especially upon the weathered surface, and the cleavage of the rock also indicates it. The cleavage face of the rock has a silky luster, due to the sericite and biotite flakes parallel to it. The rock breaks readily in various directions at angles to the cleavage, so that it is impossible to obtain well-shaped hand specimens. The schistosity in these porphyries is clearly brought out by weathering, the weathered rocks showing perfect schistosity, while fresh specimens from the same exposure, although splitting easiest in one direction, appear perfectly massive in hand specimens when broken across the schistosity. That the dynamic action was greatest along certain zones of the rock, other portions being more or less exempt, is shown by the fact that of several specimens collected with the view of obtaining different stages of alteration from different portions of the same exposure some are markedly schistose, while the least altered approach a fairly massive character.

I shall give a brief description of this least altered phase, and then

consider the changes which have taken place and the character of the rock which has resulted in the more altered phases.

The slightly schistose rock, like all the porphyries, is very fine grained and black, with a more or less silky luster on fresh fractures parallel to the schistosity. The porphyritic character is not very strongly marked. Macroscopically, comparatively few small feldspar phenocrysts are visible. Under the microscope the rock is seen to be a micropegmatitic rhyolite-porphyry in which the silica has not crystallized as quartz phenocrysts, but has remained in the groundmass. The feldspar phenocrysts are both orthoclase and plagioclase. The latter shows its usual characters, but is not present in well-formed crystals. The orthoclase, on the contrary, is well crystallized, occurring in Carlsbad twins. While some of the feldspar crystals are broken, they as a rule do not show many signs of pressure The fine-grained micropegmatitic groundmass is made up of the quartz and feldspar intergrowth and of secondary mica, both muscovite and biotite, and remnants of iron oxide. Micropegmatitic intergrowths of quartz and feldspar occur in irregularly shaped areas which frequently have a fairly large quartz at the center. Very similar irregular areas which seem to be composed altogether of unstriated feldspar also occur. These two kinds of areas compose the greater part of the rock. The mineral particles frequently show undulatory extinction. Between the micropegmatitic intergrowths one finds here and there granular aggregates of quartz and striated and unstriated feldspar. These feldspar grains, and likewise the feldspar intergrown with the quartz, are considerably altered. Sericite and biotite are present in considerable quantity. The former possesses the better crystallographic outlines, the biotite being usually found in ragged fragments. The two micas occur in the feldspars and lie between the quartz grains, but not in them. They appear to be secondary products from the feldspar. The micas lie with their long directions approximately parallel, and impart to the rock its schistose character. A few automorphic crystals of apatite were found. There occur also a few irregular grains of a dark reddish brown mineral with high single refraction, but which is isotropic. This mineral is presumed to be allanite, though conclusive tests could not be made. Some crystals of zircon were also observed. The iron oxide is evidently titaniferous, probably titaniferous magnetite. Secondary calcite is scattered through the rock in considerable quantity.

In a more altered phase of the porphyry exhibited in a number of specimens, the schistose structure is much better marked both macroscopically and microscopically. The macroscopical appearance is otherwise quite similar to the one just described. Under the microscope the phenocrysts show up well. These are rounded and shattered orthoclase and plagioclase feldspars. They lie usually with their long direction in the lines of marked schistosity of the rock. The larger crystals have been much more generally fractured than have the smaller ones, and seem to have obtained relief from strain in that way, the individual fragments not showing very strong dynamic effects. The small crystals are more or less rounded. The crushing to which the rock has been subjected has severed the fragments in a number of cases. Triangular areas on two sides of the broken or unbroken feldspars in the direction of schistosity are filled with what appear to be secondary quartz and flakes of biotite. The feldspars as a whole have undergone considerable chemical changes, the freshest being red and very cloudy. Those more altered show secondary muscovite and biotite scattered through them. The character of the triclinic feldspar could not be determined. It appears, however, to be very rich in calcium, as in some of the badly weathered sections the feldspar fragments may almost be said to lie in a calcite matrix, resulting apparently from the alteration of the feldspar and not from infiltration. No quartz phenocrysts retaining their normal character are found. There occur here and there, however, small rounded mosaics of quartz, the individual grains of which show undulatory extinction. These are evidently the result of the granulation of quartz grains, such as occur in the freshest specimens. It is well known that the quartz is more easily affected by pressure than feldspar, and Futterer[1] has shown that they may be found in a completely crushed condition, in the same section with feldspars which still retain their regular crystal contours.

The groundmass of the porphyry is made up of quartz and feldspar, in and between which lie leaflets of biotite and sericite. The holocrystalline granular mixture of quartz and feldspar is very fine grained, and the presence of the feldspar was only determined by difference in the refraction of the two minerals. No striated feldspar grains were observed. The second-

[1] Die "Ganggranite" von Grosssachsen, und die Quartzporphyre von Thal im Thüringerwald, by Karl Futterer, Heidelberg, 1890, pp. 31, 126.

ary micas appear usually in ragged flakes, though the slightly greenish-yellow sericite flakes approach crystal outlines rather frequently. The biotite is brownish-green and strongly pleochroic. A few spots of brown iron hydroxide and small heaps of grains of sphene probably indicate the former presence of titaniferous iron ore. The few crystals of apatite present are broken and separated, but otherwise retain the usual characters of this mineral.

The groundmass has a very marked schistose structure, brought out especially well by the parallel arrangement of the mica flakes. The way in which these lines of schistosity flow around the mashed phenocrysts, one line never coalescing with another, but remaining continuous, may be seen with great distinctness where the lines abut sharply against the crystal at a very obtuse angle. As the angle becomes less and less obtuse, the ends of these lines bend up slightly in the direction which would enable them to pass the crystal, and then end, so that along the face of the crystal one can follow them, as it were, in a series of steps until those lines which strike the crystal near enough the edge to flow around it bend slightly, and passing around continue on the opposite side. The fact noted by Fütterer[1] that an increased amount of sericite occurs on the two sides of the feldspar crystals parallel to the schistosity is very patent in these porphyries. The diminution in grain of quartz and feldspar seems to accompany the increase in the amount of the sericite. The slides are crossed by narrow fractures cutting the planes of schistosity, which are filled with secondary quartz, showing marked strain effects. Associated with the quartz were observed some crystals of brown rutile. In one of the more altered slides these fissures have been filled with calcite, whether or not as a replacement of the quartz could not be told.

Schistose porphyries showing the extreme alteration phases are found from N. 300, W. 300, to N. 400, W. 250, in the SE. $\frac{1}{4}$ sec. 4, T. 44 N., R. 32 W. They form a rough escarpment upon the southeast side of and near the base of a large hill, and overlook McCutcheon's Lake. The exposure is not continuous throughout, though practically so, but the unexposed parts are sufficient to prevent a perfect sequence being traced. The appearance of the rock is strongly like that of sedimentary rocks. Different bands nearly on edge may be seen, dipping 60°–90° SW. and striking N. 30° W.

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[1] Op. cit., p. 40.

At a point about 100 feet higher and three-fourths of a mile distant, on the very northwest flank of the same hill, at N. 1725, W. 775, from the southeast corner of sec. 4, T. 44 N., R. 32 W., there is a small ledge of schistose porphyry, macroscopically and microscopically similar to those to the southeast of it, and with its schistosity striking N. 20° W. and dipping 80° SW. The striking agreement in strike, dip, and general character of these two separated outcrops points to their being merely isolated portions of the same mass. There seems to be no discrepancy between the dip and strike of the schistosity and that given above for the bands.

The most striking macroscopical characteristic of these mashed porphyry flows is the occurrence of phenocrysts in a schistose and beautifully banded rock. These phenocrysts stand out clearly from the groundmass in all cases. The general appearance of the rocks is that of the well-known very dense banded hälleflintas of Elfdalen, Sweden. The bands vary in color, ranging on the weathered surface from light creamy white, through light greenish, to red and almost black. The rocks which have very light colored weathered surfaces are always bluish black on a fresh fracture, and very dense, and those weathering red are usually cream colored on freshly fractured faces. Many of the areas which appear macroscopically to be single phenocrysts are resolved under the microscope into tangled groups of individuals, though in rare cases the individuals show the imperfect radial arrangement rather frequent in medium-grained micropegmatitic rhyolite-porphyries.

The feldspar has undergone considerable alteration. In the least-changed grains there is a cloudiness caused by numerous indeterminable specks, probably of iron oxide, which give a reddish tinge to the mineral. Further changes result in the production of muscovite and epidote, with biotite in rare cases, accompanied by the obliteration of the twinning lamellæ. The greater part of the phenocrysts seem to be orthoclase, though associated with them are found pieces which show indistinct traces of the polysynthetic twinning of plagioclase feldspar. The feldspars exhibit marked strain effects, especially in their flattening into long oval and spindle-shaped areas. Some crystals have been broken and separated perpendicular to the direction of the schistosity. The spaces between the fragments are filled with secondary muscovite, quartz, and feldspar. Surrounding the phenocrysts—that is, between the phenocrysts and the ground-

mass proper—we find a mass of small angular, finely striated, limpid grains of feldspar, associated with similar grains of quartz, the two having in places between them sericitic flakes. In one especially clear case, this secondary aggregate fills half the space formerly occupied by an individual feldspar, the other half being still occupied by the remnant of the apparently simply twinned feldspar from which it was derived. (Fig. *A*, Pl. XXIII.)

While no large quartz phenocrysts were observed, a mosaic of quartz is found in small round or oval areas in various sections. The individual fragments exhibit the usual strain effects of crushed minerals. (Figs. *A*, *B*, Pl. XXIV.)

The groundmass consists of the same preponderant minerals as the schistose porphyries, which have been previously described. The accessory minerals are apatite, which is present in very small quantity, and rutile, which in one of the slides is present in very considerable quantity in the form known as "thonshiefer-nädelchen." Calcite is found in all of the slides, the amount varying very much. Those which contain a great deal have a scoriaceous-looking surface, due to weathering out of the calcite.

The flow structure mentioned as having been observed in the schistose porphyries of the Hemlock formation is perhaps of sufficient general interest to warrant a few comments. This is well marked only on one hand specimen. In this there is an alternation of pink and dark grayish-blue bands which are rarely more than a fraction of an inch thick. Some, especially the thicker bands, are remarkably persistent. Even macroscopically on the weathered surface the pinkish bands can be distinctly seen to wrap around the pink feldspar phenocrysts and oval areas of the grayish-blue part of the rock. Under the microscope the bands which macroscopically are the darkest are clear and transparent, while the pink bands are much less transparent. The microscope shows the difference in the color of the bands to be due chiefly to the fineness of grain, and brings out the flow structure even more clearly than the weathered surface. (Figs. *A* and *B*, Pl. XXIV.) Accompanying this variation of grain there is also a difference in mineralogical composition. The dark bands are composed essentially of quartz grains, with feldspar, sericite, some magnetite, considerable calcite, and rare crystals of apatite and rutile, the quartz including many black and indeterminable specks. The pink bands are very fine grained, so much

so that the clear white mineral grains composing it can not be determined, though probably both quartz and feldspar are present. These bands are darkened by innumerable black indeterminable specks and long rutile needles, with a small amount of biotite. It is possible that some of the minute biotite flakes have been mistaken for rutile needles when viewed on edge, but it is certain that these bands contain a great deal more rutile than do the others. Whether or not there is a still more essential chemical difference between the bands than that indicated by the increased quantity of rutile, was not determined.

It has become more or less common of late to attribute the banding found in metamorphosed eruptives altogether to the pressure to which they have been subjected. In the present instance I can not but consider the banding as being an original fluxion structure, with the slight original differences between the bands emphasized, as it were, by subsequent pressure. It appears highly probable that the rock was originally more or less glassy and showed a flowage structure, and that the present mineralogical character of the groundmass is due to the process of devitrification which did not destroy the banding of the original glass.

ACID PYROCLASTICS.

The only acid pyroclastic rock found was formed from the aporhyolite-porphyry. This is a true eruptive breccia. The fragments are angular to rounded in shape, weather to a pure white color, and have an exceedingly rough surface. This roughness is due to a great extent to perlitic partings, which are macroscopically visible, and give the rock an almost scoriaceous appearance. Other inequalities on the surface adding to its roughness are caused by the leaching out of feldspars, and by the fact that many of the quartz phenocrysts have fallen out of the inclosing matrix The fragments are all aporhyolite-porphyry, containing a very large proportion of quartz and feldspar phenocrysts. The cement of the breccia is aporhyolite. This contains far less numerous phenocrysts, and is, therefore, on the whole much finer grained than the fragments. The weathered surface of the cementing aporhyolite appears a bluish gray, and is very smooth compared to the scoriaceous appearing surface of the fragments already described. This difference in weathering shows the brecciated character admirably, as the finer-grained matrix stands out sharply and delimits the contours of the fragments.

Movements of the magma are shown by a flowage structure in the matrix and by the fracturing of the quartz and feldspar phenocrysts and separation of the pieces in both the cement and fragments. (Fig. *B*, Pl. XXIII.)

This eruptive breccia can be seen in its best development in the NW.-SE. trending ridge, just west of the small lake, crossed by the Chicago, Milwaukee and St. Paul track in sec. 32, T. 44 N., R. 32 W.

BASIC VOLCANICS.

The basic volcanics are considered under the main headings of lavas, pyroclastics, and Bone Lake crystalline schists.

BASIC LAVAS.

GENERAL CHARACTERS.

The basic lavas are so very characteristically developed that no one could for a moment doubt their true nature, even upon the most superficial examination. One of the nearly general characters is the presence of a well-marked amygdaloidal texture. (Figs. *A*, *B*, Pls. XXV and XXVI, and fig. *A*, Pl. XXVII.) Some of the lavas are so full of amygdules that they may be correctly said to have been scoriaceous. The amygdaloidal portions of the rock masses—which may be considered the surface parts—grade over into other portions, the interiors of the lava flows, which are, macroscopically at least, nonamygdaloidal. Owing to the homogeneous character of the basic magmas, a fluxion structure is rarely shown macroscopically, though microscopically it may be more or less well developed. Columnar jointing was nowhere observed. An ellipsoidal parting, on the other hand, is common.

NOMENCLATURE.

In a preliminary article on the Hemlock volcanics,[1] I made a brief mention of the occurrence on the Upper Peninsula of Michigan of the basic pre-Tertiary equivalents of the post-Tertiary and Recent family of basalts. Following the Danas, Wadsworth, Williams, Iddings, Kemp, Darton, and Diller, some of the most influential of the men who, in the

[1] The volcanics of the Michigamme district of Michigan, by J. Morgan Clements: Jour. Geol., Vol. III, 1895, pp. 801–822.

United States, have advocated the simplification of petrographical nomenclature, I used the term basalt, now ordinarily used for the Tertiary or post-Tertiary basic rocks. This term was, however, modified by the prefix "apo," as indicating their altered condition and the presumed presence of a glassy base.[1] This was a logical continuation of the use of the prefix as proposed by Dr. Bascom[2] for devitrified acid lavas.

More detailed studies upon the Hemlock volcanics have shown the presence of rocks which were apparently originally holocrystalline, and therefore do not belong with the altered vitreous basalts, the apobasalts, and others in which some of the glass is apparently unaltered. Consequently, since the apobasalts comprise only a portion of the Hemlock volcanics, the replacement of that term as a general heading by the older, more general, one of basalt was considered.

The use of this term is, however, not altogether satisfactory, for the rocks, while clearly recognizable as basalt derivatives, do not possess the mineralogical composition of the basalts. The term "apo" having been restricted, as above indicated, can not be applied to them, for their alteration is in many cases metasomatic and dynamic, and in most cases not devitrification. If we adopt the prefix "meta" to indicate alteration of all kinds, then these rocks could be called "metabasalts."

The terms "metadolerite," "metadiabase," etc., were proposed by Dana[3] for metamorphic dolerites, diabases, etc., and first used by Hawes[4] in the description of the altered rocks around New Haven. Recently these terms have been revived, but with a very different significance from that with which they were first used. It is proposed to designate by such terms "rocks now similar in mineralogical composition and structure to certain igneous rocks, but derived by metamorphism from something else."[5] Following this suggestion, an uralitized dolerite (diabase) would be called a metadiorite. Such a use of the term does not seem justified, and the

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[1] Loc. cit., p. 805.

[2] The structures, origin, and nomenclature of the acid volcanic rocks of South Mountain, by Florence Bascom. Jour. Geol., Vol. I, 1893, p. 828.

[3] Chloritic formation of New Haven, Connecticut, by J. D. Dana: Am. Jour. Sci., 3d ser., Vol. XI, 1876, pp. 119–122.

[4] The rocks of the "chloritic formation" on the western border of the New Haven region, by G. W. Hawes: Am. Jour. Sci., 3d ser., Vol. XI, 1876, pp. 122–126.

[5] On a series of peculiar schists near Salida, Colorado, by Whitman Cross: Proc. Colo. Sci. Soc., p. 6, footnote. Paper read Jan. 2, 1893.

objection to it can not be given better than by quoting the words which Zirkel uses in the discussion of the metamorphism of rocks:[1]

> Bei solchen metamorphisch veränderten Gesteinen ist es nicht zweckmässig, sie mit dem Namen desjenigen Typus zu belegen, dem sie durch die Veränderung ähnlich, oft blos scheinbar ähnlich geworden sind. Eine solche Bezeichnung werde nur zu missverständlichen Auffassung der von dem Gestein gespielten geologischen Rolle führen, welche niemals ausser Acht gelassen werden darf. Und so ist es denn entschieden vorzuziehen, der Benennung solcher Gesteine eine Form zu geben, in whelcher zuvörderst auch zum Ausdruck kommt, was sie früher gewesen sind, und nicht einen Namen zu wählen, der sie in erster Linie zu etwas stempelt, mit welchem sie genetisch keine Gemeinschaft haben.

Using these terms in the way suggested by Cross, attention is most pointedly directed to that variety of rock which the secondary product now resembles mineralogically, rather than to the type from which it was derived, and which in all likelihood it still resembles most closely in its chemical constitution. Whether or not a petrographer will use the term "metadiorite" or the term "metadolerite" (diabase) for a metamorphosed dolerite will depend on whether or not he prefers to emphasize the present mineralogical composition of the rock, or its original characters, and thereby its chemical constitution and genetical relations. In the present report the terms "metabasalt" and "metadolerite" are used as including all those altered rocks which demonstrably were originally basalts and dolerites.

These same strictures hold good in the case of Gümbel's term "epidiorite," when used, as it is very commonly, in the literature of the Lake Superior region and elsewhere, for rocks avowedly derived from dolerites (diabases), and characterized by the presence of fibrous secondary amphibole. It is preferred, in accordance with the above statement, to use the term "epidolerite" (epidiabase) instead of "epidiorite" for such altered dolerites. None of these rocks, unless extremely changed, would resemble chemically a diorite, and we have come of late years to rely more and more upon the chemical composition, combined of course with the mineralogical composition and textures of the rocks, to separate the various kinds from one another. As stated above, the term "epi," associated with the rock name, has come more and more to be restricted in its use solely to a rock, the epidiorite, characterized by a specific alteration product, the amphibole. In respect to this restriction to specific alteration, the term corresponds to

[1] Lehrbuch der Petrographie, F. Zirkel: 2d ed., Vol. I, p. 573.

"apo," and it is unfortunate that these two terms should have been so narrowly confined. As it is, the epi- and apo-basalts would be subordinate to and therefore included under the metabasalts, as this term is used in this report. In the first the production of secondary hornblende is characteristic; in the second the process of devitrification, and hence the original presence of a vitreous base, is the chief characteristic.[1]

METABASALTS.

All of the basalts belong to the plagioclase type. They may be most conveniently divided into nonporphyritic and porphyritic kinds, according to their most obvious macroscopical characters. There has also been found a single occurrence of a spherulitic basalt, which will be described under the head "variolite."

NONPORPHYRITIC METABASALT.

The nonporphyritic rocks possess a fine-grained or aphanitic structure and are amygdaloidal or nonamygdaloidal. There are included under this general name the microophitic-textured fine-grained pre-Cambrian basalts (diabases in part), the very amygdaloidal forms of the basalts (spilites),[2] and the melaphyres in part. In these rocks the former presence of a considerable amount of original glass is probable, and they show the various textures known as navitic, intersertal, pilotaxitic, and hyalopilitic.

With the nonporphyritic basalts there have been included some rocks which are to a considerable extent devitrified glasses, and others in which only a few microlites have developed. These last two vitreous types occur more especially in fragments in the tuffs, and are quantitatively unimportant.

Petrographical characters.—In color the nonporphyritic basalts on fresh fracture show various uniform shades of green, dark olive green usually prevailing. Much less common are purplish-black rocks, and these are much more variable in color. In one of them is seen lighter-colored schlieren, which pass over into the ordinary dark colors. The lighter-colored portions are seen on microscopical examination to be due to a smaller quantity of the iron in them and to a greater quantity of chlorite than occurs in the rest of the rock

[1] The above discussion was written and the determination to use the terms porphyry—without textural significance, as in rhyolite-porphyry—metabasalt, etc., was reached, in 1896, before the committee on petrographic nomenclature of geologic folios was appointed by the Director of the United States Geological Survey.

[2] Microscopic characters of rocks and minerals of Michigan, by A. C. Lane: Rept. State Board of Geol. Survey for 1891-92, 1893, p. 182.

mass. Where weathered, the rocks are usually covered by a thin crust, in which gray, brown, and pinkish tints prevail.

The rocks vary in texture very much, from the dense aphanitic kinds to medium fine-grained varieties. The latter are usually less amygdaloidal than are the aphanitic forms, and approach in appearance both macroscopically and microscopically the coarser-grained basalts or dolerites represented in the Michigamme district by the coarse-grained intrusives. Owing to the basic nature of the rocks, they have generally suffered much alteration, and as a result the original texture is in many cases poorly preserved. On the whole, however, it is remarkable, considering their age and basic character, how well preserved it is. Where it is preserved it varies from the micro-ophitic to the various microlitic textures, such as intersertal, navitic, pilotaxitic, and hyalopilitic, and lastly glassy. In places a flowage structure is beautifully brought out by the position of the feldspar microlites, especially around the amygdules.

The constituents present are plagioclase, light-green fibrous hornblende, epidote-zoisite, chlorite, calcite, muscovite, apatite, sphene, quartz, magnetite, and pyrite. Of these the feldspar, apatite, and iron oxide alone are original. In some places the hornblende is wanting, the chlorite then appearing in correspondingly greater quantity.

The feldspar ordinarily occurs in lath-shaped crystals showing twins of the albite type, but where the texture is fine the feldspars are microlitic, and, while showing their prominent long extension, the edges of the various crystals interfere, and the outlines consequently are less sharp.

In some of the rocks which appear to have been vitreous the feldspar forms feather and sheaf like aggregates (figs. *A*, *B*, Pl. XXVI), apparently quite similar to those described by Ransome in rocks from Point Bonita, California.[1] No reliable measurements could be made upon the microlites, and consequently their character could not be determined. The feldspar is more or less completely altered to aggregates of epidote-zoisite which have chlorite associated with them or are altered to sericite. In a number of places minute limpid spots of secondary quartz and albite are present. The very small quantity of apatite present shows its usual characters. Titaniferous magnetite ore is apparently the only oxide present. It occurs in crystals and in irregular grains, which in a few cases are not entirely altered,

[1] Eruptive rocks of Point Bonita, by F. Leslie Ransome: Bull. Univ. of Cal., Vol. I, 1893, p. 84, fig. 6.

though in most cases they are replaced by sphene. In some cases the alteration product is not well enough individualized for one to diagnose it as sphene, and it should perhaps be called leucoxene. In some of the fine-grained rocks the material in the angles between the feldspars consists predominately of grains of magnetite. This abundant magnetite renders the rock very dark, giving the rare purplish-black lavas.

The most of the hornblende has a light-green color. A lesser portion shows a decided bluish tinge, and gives fairly strong pleochroism. This resembles the hornblende, which in the coarse dolerites is undoubtedly secondary after the augite and it is considered to be secondary after the original augite in these rocks.

The original augite was presumably in most cases present in wedge-shaped pieces filling the spaces between the feldspars, and consequently the hornblende pseudomorphs never show augite outlines. No unaltered augite was observed amongst the hornblende fibers. The fine fibers frequently form a fringe beyond the original boundaries of the pieces and penetrate the adjacent feldspar. Quite frequently the secondary hornblende shows partial alteration to chlorite and epidote.

Though careful search was made for olivine or indications of its presence, no traces of it were found, and I have concluded that these basic volcanics were essentially nonolivine bearing, though it would be rash to state that such rocks did not contain some olivine.

The calcite is usually found in irregular secondary granular aggregates scattered through the rock, and evidently replaces the other minerals. Less commonly it is seen as an infiltration product along fissures.

A second form of the occurrence of calcite in the nonporphyritic metabasalts, and one not so common as the granular aggregate, is that of large porphyritic automorphic rhombohedra and scalenohedra which lie embedded in the eruptive groundmass. Such a rock, as, for instance, Sp. 32472, shows macroscopically large rhombohedral phenocrysts in a green groundmass. On the weathered surface are ferruginous rhombohedral cavities, once occupied by the carbonates. The groundmass consists of rather fresh plagioclase microlites, between which are observed some quartz, fresh magnetite crystals, and lastly chlorite flakes as alteration products of originally present bisilicates or glass, or both. The texture is undoubtedly that of an eruptive. The carbonate is more or less ferruginous, brown iron hydroxide resulting

from its alteration, and as it effervesces quite readily with cold HCl, it is supposed to be ferruginous calcite.

Sericite is found in minute flakes replacing the feldspars, and it is also found in large porphyritic plates occurring in the eruptive groundmass associated with the porphyritic carbonate above described. In some cases we find epidote in these altered basalts, in others zoisite. In a great number of instances the same individual exhibits the high interference colors of epidote and the low blue interference color of zoisite in different parts. These different portions, formed respectively of the epidote and zoisite molecules, are most closely intergrown, and I have therefore used the compound term "epidote-zoisite," indicating this fact. Associated with this, one finds in many of the specimens small mineral aggregates which merit somewhat further notice. These aggregates have a brownish-yellow color and possess a very high single and also a high double refraction. In these masses the single and double refractions of the granules composing the aggregates appear to be higher than that of epidote. In shape the aggregates vary from perfectly round, zonally arranged spheres and irregular, elongated, rounded aggregates to forms giving oblique quadratic sections. All of these aggregates are found at times included in the epidote-zoisite crystals. In a few cases the oblique quadratic sections were seen to occupy the centers of the epidote-zoisite crystals, having exactly identical outlines. It is believed that they are composed of an epidote much richer in iron than the common variety with which they are associated. This increase in iron explains the darker color and the increase in single and double refraction, as shown by Forbes.[1] Why it should appear, especially in the aggregates, can not be explained.

The chlorite does not appear to be entirely an alteration product of the secondary hornblende with which it is associated. There is usually rather more chlorite than it would seem could possibly have been formed from the alteration of the hornblende alone. In some of the rocks the larger angles, as well as the extremely fine areas between adjacent feldspars, are occupied by a very fine felt-like chloritic mass. The chlorite which is not secondary after hornblende is considered as the product of an altered glassy base.

No glass was observed in the nonporphyritic basalts occurring in large masses, but in one of the fragments of basalt in a tuff a dark chocolate-brown glass forms the matrix in which are lying well-developed plagioclase

[1] Epidote and its optical properties, by E. H. Forbes: Am. Jour. Sci., 4th ser., Vol. I, 1896, p. 30.

microlites. The glass where thick appears isotropic, but where thin appears to be full of globulitic devitrification products, which show slight polarization effects between crossed nicols.

The original presence of glass in other basalts is considered to be indicated by the occurrence of amygdaloidal cavities, with very sharply defined walls marked by accumulations of magnetite.

The character of one basalt points strongly toward its glassy condition. It is amygdaloidal, the amygdaloidal cavities being sharply defined. The groundmass contains at present no indication of the existence of any originally crystalline elements whatever. It is now a dense mass of felty chlorite and minute epidote grains. Through this mass and around the amygdaloidal cavities wind lines which are somewhat differently colored from the rest of the matrix, and seem to indicate the direction of flowage. The amygdules are not all elongated, though some are, and these agree in direction of elongation. It is really impossible to describe the groundmass so as to do justice to its appearance and convince one who has not seen it of its devitrified character. The general impression it makes is that of a devitrified glass, and the photomicrograph (fig. *B*, Pl. XXV) gives a fairly good idea of its appearance under the microscope, and will probably prove more convincing than any description that might be given. Fig. *A*, Pl. XXVII, represents a polished face of the specimen in its natural size.

Another kind of glassy basalt is represented in this district. This rock resembles the one just described, but differs from it in that it was not altogether glassy. In it one sees long, slender, much-altered feldspar microlites scattered through the matrix. These feldspars occur in needles, which fringe out at the ends. They do not give the groundmass textures usually found in the basalts, but occur in sheaves and imperfect spherulitic forms; the rock thus approaches in texture the variolites. The base in which the feldspars lie is brownish gray, and consists of recognizable chlorite, epidote, some clear mineral in minute particles, probably quartz or feldspar, or both, and aggregates of yellowish granules, which are apparently of a single kind and are so minute as not to permit of determination. The granules show very slight polarization effects under crossed nicols, and the groundmass in many places where they occur in great quantity appears almost isotropic. It seems highly probable that a large portion, if not all, of the groundmass was originally a glass. Further evidence of the originally glassy

nature of the groundmass is afforded by the groundmass, which, under the microscope, shows variable lighter and darker shades of brown, and these portions interpenetrate, forming an imperfect eutaxitic structure. Such structures are especially common in the glasses. The photomicrographs (figs. *A*, *B*, Pl. XXVI) show very well the general microscopical characters of this rock.

Chemical composition.—The following complete analysis, for which I am indebted to Dr. Henry Stokes, of the United States Geological Survey, shows the chemical composition of one of these pre-Cambrian nonporphyritic metabasalts. The rock is very fine grained and microophitic, with a marked amygdaloidal character. The amygdaloidal cavities are filled with chlorite, into which project crystals of epidote-zoisite and calcite. The altered condition of the basalt is very clearly shown by the high percentages of water and carbon dioxide. The other oxides show nothing remarkable except that the percentage of titanium oxide is quite high. On the whole, however, the analysis is very similar to those of recent fresh rocks of the same character.

Analysis of pre-Cambrian nonporphyritic metabasalt.

Constituent.	Per cent.	Constituent.	Per cent.
SiO_2	46.47	K_2O	0.21
TiO_2	1.28	P_2O_5	.13
Al_2O_3	16.28	CO_2	1.26
Fe_2O_3	3.15	Cl	....
FeO	8.96	SO_3	....
MnO	.09	H_2O at 110°	.28
MgO	6.56	H_2O above 110°	3.89
CaO	7.90	Total	100.11
Na_2O	3.64		

PORPHYRITIC METABASALT.

The porphyritic rocks are fine grained, and may be or may not be amygdaloidal. They include diabase porphyrites and porphyritic forms of the melaphyres. These last in the textures of their groundmass correspond to the labradorite-porphyrites, the equivalents of the andesite-porphyries, though more basic than they. The phenocrysts lie in a fine groundmass which shows the same kinds of texture already mentioned as having been

observed in the corresponding nonporphyritic basalts, the microophitic, intersertal, navitic, pilotaxitic, and hyalopilitic. The various basalts are connected by transition phases. The close connection between the different varieties is well shown where one passes from the fine-grained amygdaloidal rock through the fine-grained nonamygdaloidal over to the porphyritic macroscopically nonamygdaloidal type.

Petrographical characters.—As stated in the general description, these rocks do not differ essentially from the nonporphyritic basalts just described. The most important difference is in the presence of the feldspar phenocrysts, giving them a porphyritic texture.

Measurements upon the phenocrysts, made against the albite twinning plane on zone ⊥ to 010, according to the Michel Lévy method, give an average extinction angle of about 18°, which points toward its character as labradorite. However, angles obtained lower than this indicate the possibility of the association of andesine with the predominant labradorite. The feldspars show the usual alteration products. One very infrequently finds augite phenocrysts which have been completely uralitized associated with the feldspars. Other phenocrysts are now represented by masses of chlorite, with or without epidote, evidently pointing toward the basic and magnesian nature of the original mineral. As uralite is the common secondary product of pyroxene in these volcanics, the altered phenocrysts represented by chlorite masses are not believed to have been pyroxene. The original mineral was perhaps olivine. The very noticeable scarcity of augite phenocrysts in the basalts stamps them as different from the great majority of basaltic rocks and as being very similar to the basalts described by Judd,[1] from the Brito-Icelandic petrographical province, in which porphyritic crystals of augite are seldom if ever seen and in which the phenocrysts are feldspar and sometimes olivine.

The groundmass in which the phenocrysts lie have generally the same mineralogical composition and texture as the nonporphyritic rocks already described, and the two kinds are supposed to have been originally similar.[2]

[1] On the gabbros, dolerites, and basalts of Tertiary age in Scotland and Ireland, by J. W. Judd: Quart. Jour. Geol. Soc., Vol. XLII, 1886, p. 79.

[2] The groundmass of one of these porphyritic forms differs somewhat in one important respect. In it were observed numerous round areas of small size occupied by a clear white aggregate, polarizing in low gray colors. The centers of some of the areas were occupied by clumps of yellow grains, with here and there a minute flake of chlorite. Others contain only the white material, which is apparently secondary. The round areas are not sharply delimited, and hence are most probably not microamygdules. Their general appearance is strikingly like that of leucite in those plagioclase

Measurements made on the feldspar microlites of the groundmass gave 17° as the maximum extinction in zone perpendicular to 010. This angle points toward the microlites being acid labradorite. The microlites thus seem to agree essentially with the phenocrysts in composition. Flowage structure around the phenocrysts is most distinctly shown by the arrangement of the feldspar microlites. In one case in which the porphyritic texture and the flowage structure are very good, secondary actinolite crystals have developed parallel to one another and parallel to the flowage direction, giving the rock under the microscope a distinctly schistose appearance.

Chemical composition.—In the preliminary article upon these Hemlock volcanics published in 1895,[1] the occurrence of andesites as well as basalts was mentioned. This determination was based solely on the microscopical study of the rocks, and the rocks which were presumed to be andesites were those porphyritic forms which have just been described. Since the publication of that article the following analyses (Nos. 1 and 2) have been obtained of the porphyritic rocks. The rocks selected for analysis were those which appeared to be especially rich in feldspar, and, having a rather lighter color than the others, seem to be somewhat more acid than the average. These, it was thought, might have the composition of andesite.

The comparison of series of rocks derived presumably from the same magma is more profitable than the study of single analyses. This line of investigation, as followed by Rosenbusch,[2] Iddings,[3] Lang,[4] Broegger,[5] Becke,[6] and Michel Lévy,[7] has been very fruitful.

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basalts in which it is present in very small quantity, filling irregular but in general rounded areas between the other constituents. It would, of course, be impossible to base the determination of the former presence of leucite in these pre-Cambrian rocks upon such scant evidence as has been obtained. Still it is worth while to notice even such a doubtful indication of its former presence as has been mentioned above.

[1] Jour. Geol., cit. pp. 805–806.

[2] Ueber die chemischen Beziehungen der Eruptivgesteine, by H. Rosenbusch: Tsch. Min. u. Pet. Mitt., Vol. II, 1889, pp. 144–178.

[3] Origin of igneous rocks, by J. P. Iddings: Bull. Phil. Soc. Wash., Vol. XII, 1892, pp. 88–214. The eruptive rocks of Electric Peak and Sepulchre Mountain, by J. P. Iddings: Twelfth Ann. Rept. U. S. Geol. Survey, 1892, pp. 571–664.

[4] Ordnung der Eruptivgesteine nach ihrem chemischen Bestand, by H. Otto Lang: Tsch. Min. u. Pet. Mitt., Vol. XII, pp. 199–252. Beitrage zur Systematic der Eruptivgesteine, by H. Otto Lang: Tsch. Min. u. Pet. Mitt., Vol. XIII, 1892, pp. 115–169.

[5] Die Eruptivgesteine des Kristianiagebietes, by W. C. Broegger. I. Die Gesteine der Grorudit-Tinguait serie. II. Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol. Videnskabsselskabets Skrifter, I Mathematisk-naturv. klasse. No. 4, 1894; No. 7, 1895.

[6] Gesteine der Columbretes, by F. Becke: Tsch. Min. u. Pet. Mitt., Vol. XVI, 1896, pp. 308–336.

[7] Note sur la Classification des Magmas des Roches Éruptives, by A. Michel Lévy; Bull. de la Soc. Géol. de France, 3d ser., Vol. XXV, No. 4, July, 1897, pp. 326–377.

The value of such an investigation largely depends on the freshness of the rocks examined and the amount of variation. The Hemlock volcanics are all more or less altered, and the variation in character is slight. I wish, however, to call attention to the close relationship exhibited by the types of which analyses were made, and to that end the analysis of the nonporphyritic very basic appearing basalt (No. 3 of Table I) is repeated and is placed by the side of the analyses of the porphyritic ones. The complete analyses made by Dr. Henry M. Stokes, of the United States Geological Survey, are found in the first table. In the second table there is given the molecular proportion of the chief oxides, those which are not here represented having been first proportioned among them. From this table, following Rosenbusch,[1] there were obtained the figures in the third table, showing the atomic proportions of the metals present.[2]

The analyses are arranged according to the increasing percentage of calcium.

Analyses of porphyritic metabasalt.

TABLE I.—COMPLETE ANALYSES.

Constituent.	1.	2.	*a* 3.
SiO_2	47.20	52.59	46.47
TiO_2	3.30	1.36	1.28
Al_2O_3	15.36	15.93	16.28
Fe_2O_3	3.06	6.12	3.15
FeO	8.87	3.96	8.96
MnO	.20	.25	.09
CaO	5.05	5.55	7.90
MgO	4.20	5.04	6.56
Na_2O	4.72	5.79	3.64
K_2O	1.40	.67	.21
P_2O_5	.36	.15	.13
Cl	----------	----------	----------
SO_3	----------	----------	----------
CO_2	3.34	None.	1.26
H_2O at 110°	.16	.16	.28
H_2O above 110°	3.04	2.16	3.89
Total	100.26	99.73	100.11

*a*No. 3 is the analysis by Dr. Stokes of the nonporphyritic basalt, and is given for comparison.

[1] Uber die chemischen Beziehungen der Eruptivgesteine, by H. Rosenbusch: Tsch. Min. u. Pet. Mitt., Vol. XI, 1890, p. 144.

[2] Tables Nos. II and III were calculated for me by Mr. Victor H. Bassett, assistant in chemistry in the University of Wisconsin.

TABLE II.—MOLECULAR PROPORTION OF THE CHIEF OXIDES.

SiO_2	50.55	54.07	49.15
TiO_2	3.54	1.40	1.35
Al_2O_3	16.45	16.38	17.22
Fe_2O_3	3.28	6.29	3.33
FeO	9.72	4.33	9.57
CaO	5.41	5.71	8.36
MgO	4.50	5.18	6.94
Na_2O	5.05	5.95	3.85
K_2O	1.50	.69	.22
Total	100.00	100.00	100.00

TABLE III.—ATOMIC PROPORTION OF METALS.

Si	46.97	49.49	45.41
Ti	2.48	.97	.94
Al	18.07	17.73	18.80
Fe	9.87	7.67	9.74
Ca	5.42	5.63	8.33
Mg	6.25	7.09	9.58
Na	9.16	10.61	6.93
K	1.78	.81	.27
Total	100.00	100.00	100.00

As tne calcium increases there is a corresponding increase of magnesium and a diminution in potassium. A decrease in sodium is also shown if Nos. 1 and 3 alone are compared. The percentage of sodium present is rather high and with the potassium indicates a magma family rich in alkalies. The magnesium is notably high; such high percentages as we have here usually accompanying much lower percentages of alkali. It may also be noted here that the presence of the magnesium in such amounts indicates the former presence of olivine or the presence still of its alteration products, a point to which attention was directed in the microscopic description of the rocks. No. 1 is remarkable for its percentage of titanium, which is very high, even when compared with that contained in the others, which are themselves considerably above the average. All of the rocks contain a large amount of water of hydration. The percentage of CO_2 contained in Nos. 1 and 2 indicates also that they are much altered.

These analyses show that the rocks can not be classed with the typical andesites. Should they be called andesites at all, they must be classed with

the augite-andesites, and placed on the border line between them and the plagioclase basalts. It is preferred to include them under the basalts, though it can not be doubted but that if analyses of perfectly fresh rocks could be obtained, there would be found some which would incline more decidedly toward andesites than do the above specimens.

VARIOLITIC METABASALTS.

Variolites are spherulitic basalts, usually very vitreous. Since the tendency to crystallization is so much stronger in the basic than in the acid rocks, it is not surprising that they should be far less common than the corresponding acid kind. Moreover, the basic glasses are very susceptible to alteration, which naturally obscures the original characters of the rocks. This probably partly accounts for the fact that they are very infrequently observed. This spherulitic phase of the basalts is well known in Europe, but there has thus far been found only one reference to its occurrence in the United States. Ransome[1] has described a variolite from Point Bonita, California. To this there may now be added a single occurrence in the Crystal Falls district of Michigan. This variolite exposure occurs at N. 375, W. 900, sec. 4, T. 44 N., R. 33 W., in close proximity to the remnant of a basalt stream which shows well-marked flowage structure. The relations of the two rocks are not determinable from the exposures.

The rock presents a very rough mammillated surface, due to differential weathering. The varioles, being more resistant than the groundmass surrounding them, form the protuberances. These protuberances vary in shape from round to oval, and very rarely are irregular. The varioles vary also in size from minute ones to those about one-half inch in diameter, and constitute by far the greater part of the rock. These general characters may be seen on the photograph, fig. *A*, Pl. X, taken from the hand specimen. The color of the weathered surface of the rock is gray or light brown, while the fresh surface is in general a dark green. Upon the polished surface of a fresh rock the varioles have an olive-green color, with, in the majority of cases, a distinctly darker center of purplish color. Less frequently this center is lighter green than the remainder of the variole. The varioles are usually separated from each other by narrow areas of groundmass, darker than the varioles themselves, with a purplish or very dark olive-green

[1] The eruptive rocks of Point Bonita, California, by F. Leslie Ransome: Bull. Dept. Geol. Univ. of Cal., Vol. I, 1893, p. 99.

PLATE X.

PLATE X.

Fig. *A*.

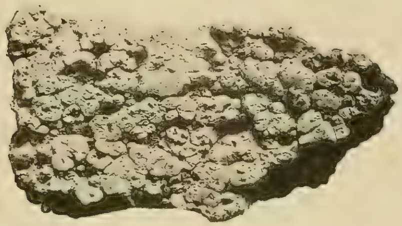
(Sp. No. 32273. Natural size.)

Photographic reproduction of the weathered surface of a variolite. This brings out very clearly the mammillated surface of the rock, which is due to the differential weathering of the varioles and of the groundmass between them. The rounded character of the varioles, and their gradation rrom those of very small to those of much larger size can readily be seen. (Desc., p. 108.)

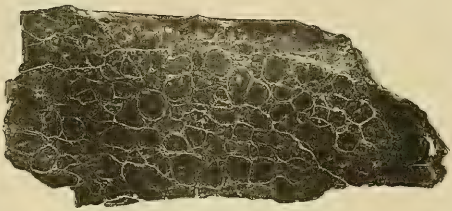
Fig. *B*.

(Sp. No. 32273. Natural size.)

Reproduction of the polished surface of a variolite. This is designed to show the circular character of the varioles, and the fact that each is separate and distinct from the one adjoining it. It can be seen that some of the varioles have very dark and others much lighter centers. (Desc., p. 108.)



(*A*)



(*B*)

(**A**) Weathered surface of variolite.

(**B**) Polished surface of variolite.

color. In places the varioles are in juxtaposition. However, they do not coalesce, but each is separate and distinct (fig. *B*, Pl. X).

The rock when examined under the microscope is seen to be extremely altered. The only original minerals present are feldspar, apatite, and possibly some magnetite.

The groundmass consists of a finely crystalline secondary aggregate of flakes of chlorite, associated with minute limpid grains, some of which are probably quartz and others feldspar. Scattered through this aggregate are grains of epidote, calcite, a few crystals of original apatite, and magnetite, and numerous dark reddish brown and black ferruginous specks.

The varioles are readily distinguishable from the matrix. From this, as well as from each other, they are invariably separated by a crack, along which reddish-brown ferruginous matter has been infiltrated. The varioles are in general much finer grained than the groundmass, and at times exhibit phenocrysts of feldspar. The composition of the varioles is the same as that of the groundmass, except that apatite is more common in them, and that in addition to the minerals mentioned as occurring in the groundmass a small quantity of original feldspar may be recognized, both as phenocrysts and as part of the groundmass of the varioles. Where these feldspars occur, they are to a great extent replaced by a mass of epidote, chlorite, sericite, quartz, and feldspar. The phenocrysts are found near the center of the varioles, and the occasional light-colored centers which were observed macroscopically are due to the presence of these altered feldspar phenocrysts. The more frequent dark centers are due to an accumulation of the dark ferruginous specks in varioles in which the phenocrysts are wanting.

No textures could be determined from the remnants of the original minerals. In one variole aggregates of secondary epidote grains and ferruginous specks lie in such a position as to produce a distinct radial arrangement. With advancing alteration, spherulites in acid rocks are frequently found to have between their radial fibers secondary deposits of epidote and ferruginous matter, which mark very clearly their radial arrangement. The similar radial arrangement in these varioles of epidote and ferruginous matter seems to point to the varioles having possessed the spherulitic character, though it is now impossible to determine the nature of the fibers forming the spherulites.

THE ELLIPSOIDAL STRUCTURE IN THE METABASALTS.

Upon examining the flat surfaces of many of the lavas one is immediately struck by their resemblance to a conglomerate formed of round bowlders, all of the same kind of rock, lying in a matrix of very small quantity and of very different color.

Fig. 7 is a sketch showing a portion of such a lava flow. I find that these ellipsoidally parted rocks have been called "massive conglomerates," and the blocks have been spoken of as "bombs" in the manuscript notes of some of the men who have worked among them. The latter term was undoubtedly due to the resemblance of the ellipsoids to the spindle-shaped pieces of lava

Fig. 7.—Sketch of the surface of the outcrop of an ellipsoidal basalt, showing the general character of the ellipsoids and matrix.

which one finds around the modern volcanoes. Ellipsoidal basalt is very common throughout the Hemlock volcanic area. It is found most frequently in isolated ledges. However, it is also associated with and grades into non-ellipsoidal varieties. In one good exposure it is overlain by a fragmental scoriaceous mass which separates it from another mass of similar ellipsoidal basalt. While the scoriaceous portion may represent the brecciated surface of a lava flow, it is not so considered, but is presumed to be a tuff deposited upon the flow represented by the ellipsoidal basalt. According to this view the ellipsoidal basalt is on the surface. In another exposure an ellipsoidal basalt overlies a bed of water-deposited clastic rock. There is no passage between the two kinds of rock. The contact between the two is an undulating one, and is marked by a mass of schistose material about 2 inches thick and similar to that which is between the ellipsoids. This particular

basalt is very dense, with only occasionally small chlorite-filled vesicles in it, and there is no true flow structure observable. The facts cited seem to show that this ellipsoidal portion was the surface of a lava flow, whether the top or the bottom is immaterial. In certain cases the ellipsoidal facies may constitute an entire flow. Where the direction of flow could with any degree of certainty be determined, it was seen that the two longer axes of the ellipsoids are in the plane of the flow.

The ellipsoids vary in size from a few inches to 6 or 8 feet in diameter, and are usually spoken of as spheroids. Attention has already been called to the incorrect usage of this term by F. Leslie Ransome, in his interesting paper on "The eruptive rocks of Point Bonita, California."[1] The outlines of the bodies are circular only in exceptional cases. On the other hand, sections in all directions through them give almost invariably ellipses, and therefore they are more properly ellipsoids than spheroids. On the surfaces exposed the long axes of the ellipses lie in the same general direction.

FIG. 8.—Sketch showing the concentration of the amygdaloidal cavities on one side of an ellipsoid, this side probably representing the side nearest the surface of the flow.

The ellipsoids are formed of a very fine-grained porphyritic or nonporphyritic rock. This is amygdaloidal or nonamygdaloidal. Where amygdaloidal, the amygdules are as a rule distributed throughout the ellipsoids, though on the whole the masses are more scoriaceous on the periphery than near the center. In exceptional cases, the amygdules are much more numerous on the west side of the ellipsoids than on the east side (fig. 8). In such cases the west sides are toward the tops of the lava flows. The ellipsoids are very commonly split up by cracks. Some of them have a roughly radiate arrangement. These may be due to the effects of contraction in the early stages of the existence of the

[1] Op. cit., p. 75.

ellipsoids. Others, and by far the greater number, have one set of lines parallel and another parallel set which in different cases cut the first set at different angles, very rarely at a right angle (figs. 8, 9). One of these sets is usually tranverse to the long axes of the ellipsoids (figs. 7, 8).

The blocks are separated from one another by a thin layer of a schistose matrix, rarely more than 3 inches in thickness, though exceptionally nearly 8 inches thick. (Cf. figs. 7 and 8 of this paper, and fig. 1 by Ransome.[1])

Since the above description of the Crystal Falls ellipsoidal lavas was written in 1896, there has appeared Sir Archibald Geikie's valuable work on the Ancient Volcanoes of Great Britain,[2] in which several similar occurrences are mentioned. His illustration of this structure on page 184, as can readily be seen on comparison, would answer, but for the absence of a well-defined schistose matrix between the ellipsoids, very well for a sketch of a Michigan pre-Cambrian ellipsoidal lava.

FIG. 9.—Ellipsoids with sets of parallel lines cutting each other at an angle.

The schistose matrix between the ellipsoids upon the weathered surface is seen to be made up of layers concentric with the ellipsoids. It is possible that these layers are not absolutely concentric in the third dimension. However, no exposure permitted of the determination of this point. Frequently certain layers seem to grade off into others of a somewhat different character. The matrix between any two ellipsoids usually separates near the center; where apparently the greatest movement having occurred the schistosity is most developed. One can often as easily knock an ellipsoid out of its encircling matrix as one can the kernel out of a nut. In some cases there is no absolutely sharp line of demarcation between matrix and ellipsoid, but a gradation from one into the other. At the places where three blocks are in juxtaposition one frequently finds, instead of a triangular space entirely filled by the matrix, in the center of the matrix a triangular area of infiltrated vein quartz (figs. 7, 8).

In certain cases the minerals which compose the schistose matrix are not thoroughly cemented and give it a somewhat friable character, causing it on weathered surface to appear granular.

In very rare cases a matrix with a distinctly brecciated character was observed, but in this as well as in the cases above described a certain degree

[1] Op. cit., p. 76.

[2] Ancient Volcanoes of Great Britain, by Sir Archibald Geikie, Vol. I, 1897, pp. 26, 184, 193.

PLATE XI.

PLATE XI.

(Sp. No. 23675. Natural size.)

This colored plate represents the polished surface of an ellipsoid with a portion of the matrix which surrounds it and separates it from the adjacent ellipsoids. The dense character of the center is nicely shown. Around this oval area we get narrow concentric zones of alternating light-green and dark-green material. The light-green material corresponds to that in the center, and represents the least-altered basalt of the ellipsoids. The dark-green areas are the chloritized basalt. Beyond this, forming the outermost greenish-gray zone, one finds the matrix, which possesses distinctly fragmental characters, though in spite of this with a marked schistose character. The schistosity of the matrix conforms to the contours of the ellipsoid.

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BASALT ELLIPSOID WITH MATRIX.

of schistosity is noticeable. The matrix between the ellipsoids varies very much in degree of schistosity, color, and composition.

The most schistose, and by far the most common variety, is the dark green matrix, which consists essentially of chlorite, epidote, and zoisite. This material is clearly the result of the chloritization and the epidotization of the original basalt constituting the ellipsoids, for we see it alternating with bands of and grading into the less altered basalt. (Pl. XI.)

A second facies of the matrix is that which possesses only a moderate degree of schistosity, and appears at times almost massive. This matrix may be light colored, almost white or greenish, or a dark bluish-black. It is medium grained or aphanitic. The light-colored matrix consists essentially of quartz and calcite. When a little chlorite or epidote is present, it has a greenish tinge. The very dark variety consists of quartz and siderite, colored with minute particles of iron oxide. The quartz-calcite or quartz-siderite aggregates owe their origin to essentially the same processes, calcification, or sideritization, respectively, followed by silicification of the original basaltic material. They are therefore briefly described together here. Their characters and origin will be found discussed in detail on page 130 et seq. Some of the peculiar characters of this matrix are illustrated in fig. *B*, Pl. XXVII.

The least common variety of matrix found between the ellipsoids is of a light greenish-gray or brownish color, and possesses a noticeably brecciated character (fig. *B*, Pl. XXXIV, and Pl. XI), but with at the same time a certain degree of schistosity. Its characters are best seen under the microscope by moderate magnification. Its brecciated character is then well shown.

The fragments of such a matrix are of all sizes and are angular. They show quite commonly a separation into zones. The fragments now consist of chlorite and epidote, and in the fragments with zonal arrangement chlorite in exceedingly fine flaky aggregates occupies the center and epidote the outside. Now and then there may be several alternating zones of chlorite and epidote. In all cases both epidote and chlorite are present in the zones, but the one mentioned is in great quantity, while the other is very subordinate. The epidote is very commonly the dark ferruginous kind mentioned on page 101, and marks off the outer limits of the fragments. Now and then the limits are outlined by a zone of brownish ferruginous material, whose exact character could not be determined. The fragments of the breccia show now neither original minerals nor textures. To judge from

the uniform character of the zones in the fragments, the original material was very homogeneous, most probably a basalt glass.

The spaces between the fragments are occupied by a finely crystalline aggregate of quartz and chlorite, with a small amount of epidote. This aggregate outlining the original fragments owes its origin most probably to the process of infiltration. The long axes of the quartz grains and chlorite flakes in this aggregate usually show a general parallel arrangement. Moreover, the long directions of the fragments are in general parallel with each other, and with the quartz-chlorite aggregate between them. This parallelism results in giving an imperfect schistosity to the matrix. The schistosity of the matrix is in general parallel to the contours of the ellipsoids which it surrounds.

Origin of the ellipsoidal structure.—Ellipsoidal structures similar to those just considered have been described by various authors.[1]

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[1] On columnar, fissile, and spheroidal structure, by T. G. Bonney: Quart. Jour. Geol. Soc., Vol. XXXII, 1876, pp. 140–154.

Ueber mechanische Gesteinsumwandlungen bei Hainichen in Sachsen, by A. Rothpletz: Zeitschr. deut. Geol. Gesell., Vol. XXXI, 1879, pp. 374–397; Vol. XXXII, 1880, p. 447.

Report on the geology of northern New Brunswick, by R. W. Ells: Ann. Rept. Geol. and Nat. Hist. Survey of Canada, 1879–80, D, p. 24.

E. Dathe: Jarb. K. preuss. geol. Landesanstalt, 1883, p. 432.

K. Dalmer: Cf. Zirkel Pet., Vol. II, p. 650.

Report on the geology of the Lake of the Woods region, by A. C. Lawson: Geol. and Nat. Hist. Survey of Canada, 1885, CC, pp. 51–53.

The greenstone-schist areas of the Menominee and Marquette regions, by G. H. Williams: Bull. U. S. Geol. Survey, No. 62, 1890, pp. 137, 166–168, 175, and 203.

On the variolitic rocks of Mont Genevre, by G. A. J. Cole and J. W. Gregory: Quart. Jour. Geol. Soc., Vol. XLVI, 1890, pp. 295–332.

On a variolitic diabase of the Fichtelgebirge, by J. W. Gregory: Quart. Jour. Geol. Soc., Vol. XLVII, 1891, pp. 45–62.

The Kawishiwin agglomerate at Ely, Minnesota, by N. H. Winchell: Am. Geol., Vol. IX, 1892, pp. 359–368.

The eruptive rocks of Point Bonita, California, by F. L. Ransome: Bull. Dept. of Geol. Univ. of Cal., Vol. I, 1893, pp. 71–114.

Editorial note on the above paper, by N. H. Winchell: Am. Geol., Vol. XIV, 1894, p. 321.

The geology of Angel Island, by F. L. Ransome: Bull. Dept. Geol. Univ. of Cal., No. 7, 1894, p. 202.

Variolite of the Lleyn and associated volcanic rocks, by C. Raisin: Quart. Jour. Geol. Soc., Vol. XLIX, 1893, pp. 145–165.

On a radiolarian chert from Mullion Island, by H. Fox and J. J. H. Teall: Quart. Jour. Geol. Soc., Vol. XLIX, 1893, p. 211.

On greenstone associated with radiolarian chert, by J. J. H. Teall: Trans. Roy. Geol. Soc. of Cornwall, 1894: Cf. Rosenbusch, Mikroskopische Physiographie, 3d ed., p. 1064.

The volcanic rocks of the Michigamme district, by J. M. Clements: Jour. Geol., Vol. III, 1895, p. 808.

The geology of Point Sal, by H. W. Fairbanks: Bull. Dept. Geol. Univ. of Cal., Vol. II, 1896, p. 40.

Geology of the Fox Islands, Maine, by G. O. Smith, 1896, pp. 16–18.

The Ancient Volcanoes of Great Britain, by Sir Archibald Geikie, London and New York, 1897, pp. 26, 184, and 193.

Various attempts have been made to explain this peculiar structure. Bonney, Dathe, and Raisin regard contraction as the force which produced the rounded masses.

Dathe and Dalmer show by the presence of the concentrically arranged amygdules that the ellipsoids were units, and were formed before solidification of the rock. This arrangement of the amygdules, as well as the arrangement illustrated in fig. 8 on page 113, precludes at once the idea that the structure owes its origin to the well-known weathering process which by exfoliation produces spheroidal blocks.

Rothpletz and Williams look upon the ellipsoids as due to mechanical forces which ground down the angles and edges of a fractured lava flow, the idea of both authors apparently being that the fractures were long subsequent to the movement of the flow.

Ells and Lawson mention the structure as concretionary.

Winchell considers the cases described by him as agglomeratic accumulations.

Cole and Gregory see in the masses evidence of lavas rolling over among themselves. In the later paper, published alone, Gregory definitely states that the lava first contracted into spheroids, which then rolled over one another.

Ransome explained the Point Bonita occurrence as a basalt which flowed "as a viscous pahoehoe, one sluggish outwelling of lava being piled upon another to form the whole mass of the flow."[1] In the description of the basalts, he writes: "A certain amount of crushed and sheared material fills the interstices between the spheroids and seems to be made up of comminuted fragments of the same rock. It is, however, too crumbling and too full of secondary products for a satisfactory determination."[2] In the second occurrence, in a fourchite (augitite?), the relations of the rocks are such as to prove "conclusively that such structure can not be rigidly restricted to surface flows, although it is still believed that lavas exhibiting it must have been erupted under very nearly surface conditions."[3]

Teall agrees with Ransome in comparing the ellipsoidally parted masses of basalt to pahoehoe lava. Teall concludes that such ellipsoidally parted basalts are submarine flows.

In a recent paper Smith has described from certain volcanics bodies

[1] Op. cit., p. 112. [2] Op. cit., p 78. [3] Angel Island, op. cit., p. 202.

which in cross section give elliptical figures, but whose indeterminate downward extension shows them to be columns. The rounding of the columns, which were presumably originally prismatic, he ascribes to dynamic action. He also suggests that ellipsoidal masses could result from a similar dynamic modification of a mass of lava parted into shorter prisms, or even ellipsoids.

In the description of the eruption at Santorin, Fouqué[1] mentions a viscous lava exuded in the form of a mass of blocks. These blocks, tumbling over one another as the mass is pushed from behind, have accumulated in a rough pile, Pl. XII. Fouqué climbed these piles of block lava shortly after their production, and noticed the breaking off of pieces from the sides, due to the cooling and contraction of the individual blocks.[2]

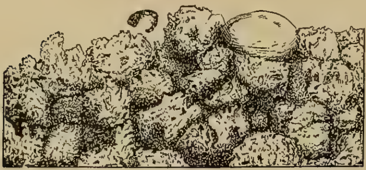

Fig. 10.—Reproduction of illustration of aa lava, after Dana (Characteristics of Volcanoes).

In general this character agrees well with that of the aa lava of Hawaii, as described by the late Prof. J. D. Dana.[3] He describes the formation of the blocks as due to the slow forward movement and contemporaneous breaking up of the viscous lava. The surface contrasts with the ropy surface of the more liquid pahoehoe. The aa is as a rule compact as compared with the pahoehoe, though the exterior "is roughly cavernous, horribly jagged, with projections often a foot or more long that are bristled all over with points and angles." From the illustrations of this lava (see fig. 10, taken from Dana) the blocks may be seen to be, while irregular, still in general distinctly rounded. This is the shape which viscous material would naturally tend to take when subjected to the rolling action attendant upon the onward motion of the stream of which they form an outer portion, or in certain cases the entire thickness. This is clearly shown from the following quotation from Dana's description of the constitution and condi-

[1] Santorin ét des Eruptions, by F. Fouqué: Paris, 1879, Chap. II. Compare especially Pls. VIII and XIII.

[2] Op. cit., p. 54.

[3] Characteristics of Volcanoes, by J. D. Dana: New York, 1890, pp. 9, 241, and Am. Jour. Sci., 3d ser., Vol. XXXIV, 1887, p. 362.

"An *aa* or *arate* lava stream consists of detached masses of lava as far as is visible from the outside. The masses are of very irregular shapes and confusedly piled up to nearly a common level, although often covering areas many miles long and half a mile to a mile or more wide. The size of the masses in the coarser kind varies from a few inches across to several yards."

MOUNT GIORGIOS, VIEWED FROM ITS WEST FLANK, IN APRIL, 1866, ILLUSTRATING THE CHARACTERISTIC BLOCK LAVAS.

Reproduction of Pl. VIII from "Santorin et ses Eruptions," by F. Fouqué.

tion of the aa stream when in motion:[1] "(1) A mass of rough blocks outside, precisely like the cooled aa stream; (2) the motion extremely slow, indicating a semifluid condition beneath; . . . (5) the blocks of the upper part of the front, as the stream creeps on, tumbling down the high slope, owing to retardation at bottom from friction, and thus a rolling action in the front part."

Dana describes the gradation of pahoehoe into aa lava. He writes, "a lava stream may change from the smooth-flowing or pahoehoe condition to the aa and back again to the smooth-flowing."[2]

Platania[3] describes from Aci-Trezza and Aci-Castello basalts with globular structure. The interspaces between the globes are filled with silt, or silt and tuff, and the exterior of some of these globes presents a thin vitreous cracked crust (cf. p. 117). These globular basalts are apparently but a modification of the block or aa lavas described by Fouqué and Dana, in which the separate portions of the lava have assumed a sufficiently rounded character to be called globes. However, Platania's further descriptions show this term to be clearly inapplicable unless the word "globe" is used with considerable latitude.

The Santorin block lava, the Hawaiian aa lava, and the Aci-Castello globular lava are all products of a slowly-flowing comparatively viscous mass. They will in the further description be included under the general term "aa lavas," as this is the most common form of occurrence of such viscous lavas.

The ellipsoidal basalts of the Crystal Falls district appear to be comparable to the Hawaiian aa lava and block lavas of the kind described by Fouqué. The lavas have subsequently been exposed to great pressure and are considerably altered. The most obvious character of these masses, their rounded outline, is believed to be due to considerable extent to the onward motion of the stream as described by Dana.

Contraction caused by cooling, accompanied by falling off of fragments from the outside, as observed by Fouqué[4] in the Santorin block lava, would also tend to round blocks which were originally angular. (Pl. XI.) In

[1] Characteristics of Volcanoes, by J. D. Dana, New York, 1890, p. 242; and Am. Jour. Sci., 3d ser., Vol. XXVI, p. 100.

[2] Am. Jour. Sci., 3d ser., Vol. XXXIV, p. 363.

[3] Geological notes of Acireale, by Gaetano Platania: The Southern Italian Volcanoes, H. J. Johnston-Lavis, editor, Naples, 1891, Chap. II., p. 41.

[4] Op. cit., p. 54.

some cases the separate portions of the lava may have been originally nearly globular, similar to the ones described by Platania. The ellipsoidal basalts, however, are so common in the Crystal Falls district and such globular basalts are so rare that this peculiar form is not considered worthy of much consideration in the further discussion, the first two kinds being chiefly the forms from which these were derived.

The lava blocks rolling over one another as the lava stream advanced, would lie with their axes in all positions, but pressure and the onward movement of the flow would, in the lower portion of the stream at least, be sure to produce from the blocks ellipsoidal bodies with their two longest axes corresponding—the one to the direction of flow and the other to the lateral extension of the stream. After the stream ceased to flow and the lava solidified, there would be a gradation from the ellipsoidal into the non-ellipsoidal portion of the flow.

An aa stream, such as described and shown in fig. 10, when subjected to great pressure subsequent to burial beneath thick deposits, would be compacted by the breaking up of the jagged outer portions, which, falling down, would fill the spaces between the blocks. This broken material filling the spaces would be most exposed to movement and to the action of percolating waters. It would consequently be very much altered, as in the material described above (p. 119) by Ransome. Such alterations would result in producing a matrix of exactly the same general composition as the altered ellipsoids. It is the common case of metamorphic action producing from rock masses of essentially the same chemical composition, but of different character, similar end products. This brecciated character of parts of this matrix is well shown in parts of Pl. XI, and fig. *B*, Pl. XXXIV. In this case silica has been introduced, filling the spaces and marking out the outlines of the fragments. Where mashing has been excessive, the outlines of the fragments are obliterated and the matrix rendered schistose. There may even be a gradation from the schistose matrix into the altered basalt of the ellipsoid, which at the center is massive.

Let me recall the statement made on previous pages concerning the distribution of the amygdaloidal cavities in the ellipsoids. This is one of the characteristic features of the lavas. We have (1) amygdaloidal cavities distributed about evenly throughout the ellipsoids, the cavities being somewhat smaller in the center than upon the periphery; (2) the cavities are

concentrated upon the periphery with few or only microscopical cavities in the center; (3) they are concentrated on one side of the ellipsoid, this side representing apparently that side of the ellipsoid turned toward the upper surface of the lava stream. The following explanation is offered for this difference in occurrence. The distribution of cavities is determined by three factors: The viscosity of the lava; the difference in specific gravity between the bubbles filling the cavities and the lava; and the expansive action of the gas. In the case of (1) the ellipsoids are considered to have consisted of lava in a viscous condition through which the gas pores formed, but in which, owing to the high degree of viscosity, they remained nearly or quite in the positions in which they were formed. Here viscosity was the determining factor. In case (2) the gas pores, influenced chiefly by the expansion of the gas, collected upon the periphery—just as, for instance, in the steel ingot while the center is compact the outer surface is porous. The lava in this case was probably less viscous than in the former. In the last described condition of distribution (3), where the gas cavities are on one side, which is the upper surface, the lava was still less viscous than in the preceding cases. Here specific gravity was the controlling factor, and, as a result of the specific gravity and the less viscous nature of the lava, the gas bubbles rose and collected upon the upper surface.

The explanation of the ellipsoidal basalts which has been offered—viz, that they are comparable with aa or block lava—seems to offer a ready explanation for all of the observed characters. On the whole, the ellipsoids owe their origin and certain peculiarities to the viscous nature of the lava. They possess also characters which are due to contraction, others which are due to original flowage, and still others which are the result of subsequent orogenic movements.

In certain places we may find the ellipsoids only half formed—that is, attached by one side to the main unbroken part of the lava flow, the other side showing a rounded outline. This probably represents a place where the aa grades into a pahoehoe or smooth-flowing form. Such an instance is possibly that illustrated by Ransome.[1]

Both Ransome and Teall compare the ellipsoidal basalts studied by them with pahoehoe lava. The latter also suggests a submarine origin for the basalts studied by him. It should be noted that pahoehoe lava in its

[1] Point Bonita, op. cit., fig. 2, p. 77.

typical occurrence in Hawaii is found only in dry places, whereas the aa is confined to those parts of the lava stream—which in other portions of its course is perhaps developed as pahoehoe—where it crosses moist valleys or other depressions presumed to have contained a considerable amount of moisture.[1]

In the case of some of the block lava of Santorin described by Fouqué,[2] with which this may be compared, the conditions were such that the lava practically welled up through the water.

From Dana's description it appears that lava in the pahoehoe form can not exist in the presence of moisture, being changed to the aa form. It would thus seem that Teall's statement of a submarine origin for the pahoehoe lava is untenable.

Wherever the ellipsoids have been studied in the Crystal Falls district, they have been found to exist as separate units, thus indicating the extremely viscous character of the lava. It would seem that the analogy between these basalts and the aa or block lava is much greater than that which exists between them and the pahoehoe or smooth-flowing lava.

AMYGDALOIDAL STRUCTURE.

The amygdules in the basalts are composed of nearly the same minerals as those which occur secondarily in the rock mass itself. Arranged in order of frequence of occurrence, they are as follows: Chlorite, epidote-zoisite, quartz, calcite, feldspar, iron oxide, and biotite. An amygdule may consist entirely of one of the above minerals, or, as is most commonly the case, of two or more of them. In the latter case the minerals are usually arranged in concentric layers. The nonoccurrence of zeolites is very noticeable. Their absence from these Huronian volcanics is especially striking since they are so common in their altered modern equivalents, and also occur in basalts as old as those of the Keweenawan of Lake Superior[3] and of the South Mountain of Pennsylvania.[4]

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[1] Cf. Characteristics of Volcanoes, by J. D. Dana: New York, 1890, p. 243.

[2] Op. cit., Chap. II.

[3] Paragenesis and derivation of copper and its associates on Lake Superior, by Raphael Pumpelly: Am. Jour. Sci., 3d ser., Vol. II, 1871, p. 188; also Geol. Survey, Michigan, Vol. I, part 2, 1873, pp. 19–46; Geol. of Wisconsin, Vol. III, 1880, p. 31.

The copper-bearing rocks of Lake Superior, by R. D. Irving: Mon. U. S. Geol. Survey, Vol. V, 1883, p. 89.

[4] The volcanic rocks of South Mountain in Pennsylvania and Maryland, by G. H. Williams: Am Jour. Sci., 3d ser., Vol. XLIV, 1892, p. 491.

It is also of interest to notice that there is a total absence of indications of copper in these Huronian volcanics, as well as in those of the Penokee-Gogebic, although it is associated with similar rocks in the areas above referred to as well as in many others.

The amygdules, with the exception of those of chlorite and of biotite, are of much lighter color than the body of the rock, and from a short distance give the rock the appearance of a porphyry. Weathering gives the rock a different appearance according to the materials filling the vesicles. Where these weather readily they are removed and the rocks become scoriaceous. Where, on the other hand, as frequently happens, the vesicles are filled with quartz, the matrix weathers more rapidly and the rounded quartz cores stand out on the face of the rock like the quartz pebbles from the softer matrix of a conglomerate.

In a few cases hematite is disseminated through the quartz of the amygdules, giving it the bright-red color of jasper, and by some these amygdaloidal fillings have been taken for included jasper pebbles.

Careful study was made of the filling of the vesicles with the object of determining the order of deposition of the minerals. However, it was found that the amygdules in a single slide contain very different fillings, one chlorite, another calcite, a third epidote, and so on; and that even in the same slide the relations are not always the same, a mineral which here occupied the center of an amygdule being found there on the periphery. Moreover, the same mineral species was found at times occupying the outside and the center of the same amygdule.

It is clear that the fillings are not the result of a solution common to all the lavas, but that the same kinds of solutions were active in the various lavas at different times and even in the same lava at different times. However, the conclusions reached were that the chlorite was generally the first product deposited and the quartz usually the last. From the study of the related amygdaloids upon Keweenawan Point, Pumpelly[1] long ago reached the conclusion that chlorite was the earliest product of alteration—hence we may conclude the first to be deposited in the amygdaloidal cavities; and that the latest mineral deposited in the cavities, omitting copper from

[1] The paragenesis and derivation of copper and its associates on Lake Superior, by Raphael Pumpelly: Am. Jour. Sci., 3d ser., Vol. II, 1871, p. 29.

Metasomatic development of the copper-bearing rocks of Lake Superior, by Raphael Pumpelly: Proc. Am. Acad. Arts and Sci., Vol. XIII, 1878, p. 307.

consideration, was quartz, the tendency naturally being to replace more alterable with less alterable minerals.

Flattening of amygdaloidal cavities.—In some of the amygdaloids (fig. *B*, Pl. XXV) the cavities retain their circular shape, as though the rock had not flowed to any great extent. More commonly the cavities are drawn out into irregular (fig. *A*, Pl. XXV) or lenticular shapes, the long axes agreeing with the direction of flowage in case their deformation resulted from this, or with the direction of schistosity in those cases where the rocks have been extensively mashed. In some cases the cavities have been so extremely flattened that the amygdules appear almost the shape of a melon seed, showing a mere streak of chlorite in the sections cut perpendicular to the schistosity, and in the planes of schistosity large lustrous oval areas.

In some few of the basalts the groundmass immediately surrounding the amygdules is characterized by an accumulation of ferruginous matter. In most cases, however, this part of the groundmass does not differ in any respect from the rest of the groundmass of the basalts and points to a very gradual cooling.

ALTERATION OF THE BASALTS.

The descriptions given are of the freshest and most characteristic basalts. As already explained, the mineral constituents in even these freshest ones have undergone a very far-reaching alteration. The rocks which show a more advanced stage of alteration exhibit merely a difference in degree rather than in kind, and the minerals which result are in all cases the same. They are uralite, actinolite, epidote-zoisite, chlorite, white and brown mica, calcite, sphene, quartz, and feldspar.

The amount of these secondary minerals varies greatly, showing that the alteration products resulting from the same kind of original rock may differ very materially according to the process of metamorphism.

In a general way the alteration of the basalts, as observed under the microscope, has taken the following course: Even in the rocks nearest their original condition the augite has largely changed to uralite. The vitreous base, if any was present, has become devitrified. Rocks in this stage of change still show the more important external characters of igneous rocks, including in many cases those which are characteristic of glass. Some of the rocks at this stage are light gray to green and exceedingly tough. Many of these break with a ringing sound almost like phonolites. At a

further stage of change the feldspars are partly altered to a granular aggregate of various minerals. In ordinary light the textures of igneous rocks are still preserved, but in polarized light none are seen, with the exception of amygdules which may be present. In some cases even these are obliterated, and the original nature of the rock can only be determined from its mode of occurrence and its association.

Further changes may produce rocks which consist practically of calcite, and may be nearly white.

Again, from these basic rocks there may be produced in extreme cases, by a process of silicification, a rock which consists practically of pure silica.

Description of some phases of alteration.—As illustrating some cases in which the same alteration products, but in different proportions and arrangement, give rocks differing very essentially, there are given the following brief descriptions of some of the rocks studied.

The flow structure was noted as being exceedingly well developed in the microlitic rocks, and in some of them the production of amphibole needles and chlorite flakes has taken place parallel with the long direction of the feldspar microlites (the flowage direction), thus developing, in combination with the unaltered microlites, a well-marked schistosity. The feldspars are still fairly well preserved.

In another case the feldspar microlites have become completely sericitized, the interspaces between them being occupied by epidote, chlorite, and iron oxide. The preservation of the feldspar shapes, showing in ordinary light the igneous texture of the rock, gives the only clue to its original nature. (Figs. *A* and *B*, Pl. XXVIII.) In some of the basalts the feldspar is replaced chiefly by epidote-zoisite, and, as in the above case, such rocks show their igneous character only when examined in ordinary light or by uncrossed nicols. (Figs. *A* and *B*, Pl. XXIX.)

In still other rocks calcite is very abundant. Its occurrence in porphyritic rhombohedra and scalenohedra was mentioned in the description of some of the rocks. These porphyritic calcites have thus far been found only in the fine-grained microlitic types of groundmass, the coarser ophitic rocks having it only in the usual granular aggregates. Muscovite, occurring in large porphyritic plates, conforms in occurrence to the calcite. When muscovite is present, calcite is found associated with it in every case, though the calcite may occur alone, and this latter is also by far the more

common. These crystals give a secondary porphyritic character to the lavas, and the microscopical appearance of the rocks varies somewhat according to the occurrence of the calcite. Such rocks, for instance where the rhombohedra occur, look on fresh surface by rapid examination like porphyrites in which the feldspar sections are all quadratic. In the others the scalenohedral sections resemble in general lath-shaped feldspar phenocrysts lying scattered in all directions on the surface of the rock.

Another case of extreme alteration is shown in a light greenish-gray, much-altered schistose rock from sec. 21, T. 46 N., R. 32 W. Upon the weathered surface long grooves are noticed—one measuring 60 mm. long by 5 mm. wide—which on the fresh surface are filled with calcite. On faces perpendicular to the long extension of such grooves they appear as narrow slits, with the long direction of the slit, that is, the width of the groove, agreeing with the schistosity. These are clearly flattened amygdaloidal pores, and but for them the igneous nature of the original rock could not have been determined. The extreme flattening of these amygdaloidal cavities and the schistose nature of this rock produced from an original volcanic, points toward mashing as one of the causes, if not the main cause, of its present characters. It is now composed of fairly large automorphic actinolite individuals, a very small amount of biotite and chlorite flakes, and masses of grains of quartz, calcite, epidote-zoisite, magnetite, with ilmenite and hematite in thick plates filling in the spaces between the actinolites. If any feldspar was originally present, it is now entirely concealed by the calcite and epidote-zoisite.

The calcite phenocrysts are found in the fairly fresh lavas. They are beautifully automorphic and are certainly not replacement pseudomorphs of some original phenocrysts, but replace the various minerals of the fine-grained mass. Moreover, it is clear that they were formed subsequent to all dynamic action, as their crystal outlines are perfect and they never show any evidence of pressure. This is so even in those cases where the amygdules which have been markedly elongated are filled with calcite The process of replacement could not be followed, but it is evidently connected with the development of chlorite, those rocks in which a great deal of the calcite occurs having chlorite developed instead of actinolite.

In other sections in which the amount of porphyritic calcite or calcite and muscovite is much greater than in the rocks just described, the amount

of chlorite, iron oxide, rutile, and quartz is also greater. The quartz is in very fine grains. The presence of the feldspar can only be determined with difficulty, and usually only on the edges of the sections, as the large amount of chlorite in the center conceals it. The textures caused by the feldspar and the amygdules still indicate the original character of such extremely altered stages. Figs. *A* and *B*, Pl. XXX, illustrate such a rock, showing the secondary porphyritic muscovite and calcite, and also the original amygdaloidal character.

A still further stage of alteration gives a rock whose groundmass is composed of the finest-grained quartz and of grains and needles of brown rutile (anatase?). In this lie rhombohedra of ferruginous calcite, plates of muscovite, and irregular flakes of chlorite. The rock is macroscopically gray, hard, and quartzitic, has a ferruginous, brown, weathered crust, effervesces with cold HCl, and yet shows its volcanic character by the numerous beautiful amygdules. These stand out on the surface like pebbles in a conglomerate. In some cases the weathering brings out the concentric character of the filling very nicely. For example, some may be seen in which the core is quartzitic, and is standing surrounded by a ring-like depression, showing by difference in the weathering the different character of the mineral filling. Under the microscope the only amygdules which happened to be cut by the section were found to be filled with fine-grained quartz, with chlorite in automorphic flakes at the center of the amygdules, and lying in the quartzitic mass. The macroscopical appearance of some of the amygdules shows that just the reverse condition also exists, that is, that quartz forms the centers and chlorite surrounds it.

The extreme stage of such an alteration is a rock which shows no amygdules macroscopically or microscopically, but is otherwise like the groundmass of the above last-described rock. It would be impossible to determine the original character of such a rock except by its association.

The extremes of texture obtained in the alteration processes are, on the one hand, a porphyry with eruptive groundmass and secondary phenocrysts; on the other, a porphyritic schist, in which all elements are secondary. These extremes are connected by gradation varieties, in some of which the calcite and muscovite approach more closely to the size of the elements composing the groundmass, and which consequently approach the ordinary schists in structure.

In these rocks the porphyritic characters are unquestionably due to the production of secondary phenocrysts of mica (muscovite) and calcite, not by contact metamorphism but by dynamic action.[1]

It has not been found possible to determine definitely from a study of the specimens, in many cases from widely separated exposures, on which the above observations were made, whether the process which has taken place in the production of such rocks has been a combination of calcification and silicification, or a process by which carbonate is being replaced by silica or the reverse. The replacement of carbonate by silica, as shown by Irving and Van Hise,[2] has taken place extensively in the case of the ferruginous carbonates of the Penokee-Gogebic and Marquette iron ranges of Wisconsin and Michigan. The automorphic character of the carbonate would seem to point toward calcification as the controlling process in the Crystal Falls rocks.

Though the presence of quartz as the last filling of the amygdaloidal cavities points toward silicification as being the process which would eventually predominate, it is most probable that both processes of calcification and silicification are active; but whether the one or the other is the controlling one depends upon the depth of burial of the rocks which are altering.

This statement appears to be supported by the facts to be described in the following pages. The following observations, which were made upon sections taken from an ellipsoidally-parted basalt occurring on top of the hills to the west of and overlooking Mansfield, illustrate the changes which take place in the passage from the massive rock of the ellipsoids into the schistose material of the matrix. The change is one of increasing alteration. This alteration is largely one of carbonation followed by silicifica-

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[1] Metamorphism of clastic feldspar in conglomerate schist, by J. E. Wolff: Bull. Mus. Comp. Zool., Vol. XVI, 1891, pp. 173-183, Pls. I-XI. Cf. also Wolff on Green Mountains, Mon. U. S. Geol. Survey, Vol. XXIII.

Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, p. 692.

Phases in the metamorphism of the schists of Southern Berkshire, by W. H. Hobbs: Bull. Geol. Soc. Am., Vol. IV, 1894, pp. 169-177.

[2] Origin of the ferruginous schists and iron ores of the Lake Superior region, by R. D. Irving: Am. Jour. Sci., 3d ser., Vol. XXXII, 1886, pp. 255-272.

The iron ores of the Penokee-Gogebic series of Michigan and Wisconsin, by C. R. Van Hise: Am. Jour. Sci., 3d ser., Vol. XXXVII, 1889, pp. 32-48.

The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Tenth Ann. Rept. U. S. Geol. Survey, 1889, pp. 341-507; Mon., Vol. XIX, 1892, pp. 254-257.

tion. It may be characteristic also of basalts with no ellipsoidal parting, but it has been possible to follow the successive changes only in the ellipsoidal basalts. This is due to the fact that each ellipsoid shows all stages from the comparatively fresh material of the center to the much altered material on the periphery, and to the most altered basaltic material forming the so-called matrix surrounding the ellipsoidal bodies (p. 114).

The freshest part of the interior of an ellipsoid from this occurrence is a very fine-grained micro-amygdaloidal basalt, in which in ordinary light lath-shaped feldspar microlites can be readily distinguished. Upon close examination the feldspars are found to be much altered, and in many cases their crystal outlines are almost completely filled out by grains of calcite and flakes of sericite and chlorite in a quartz-albite (?) aggregate. The spaces between the feldspar laths are now occupied by large crystals of epidote-zoisite, grains of iron oxide, a few flakes of chlorite, and innumerable small round yellowish-brown and greenish indeterminable bodies. The epidote-zoisite crystals also include large quantities of the brown and green globular bodies, showing that they were produced previous to the epidote-zoisite. The substance in which this aggregate is embedded could not be determined, as the aggregate is either so dense that nothing could be discerned or else underlain by feldspar. In the last case the substance is seen to be clear white. The minerals mentioned, with the exception possibly of the iron oxide, have evidently been produced secondarily from the substance or substances originally filling the spaces between the feldspars. Nothing points toward the original substance or substances having been crystallized, and I am inclined to believe that it was glass.

Toward the exterior of the ellipsoid the rock is more altered. The zoisite and calcite are more abundant. The calcite occurs in the spaces between the feldspars, as well as occupying parts of their outlines. (Figs. *A* and *B*, Pl. XXXI.) All of the other products drop into the background, owing to the fact of nonproduction, or concealment by the zoisite-calcite aggregates.

Still nearer the exterior of the ellipsoid the calcite frequently fills the spaces once occupied by the feldspars with long scalenohedral crystals, which in a way maintain the original igneous structure. The calcite is, however, not confined to these feldspar areas alone, but, as stated above, also occurs between them.

The matrix, representing the most altered phase, is a granular aggregate of calcite, in which one may here and there discern small clear limpid grains of secondary quartz and feldspar (?) and flakes of chlorite. The calcite includes in considerable quantity the globular bodies mentioned. These are found also in the spaces between the calcite grains, as though pushed away from the grains as they crystallized.

Some of the calcite in the first stages of the alteration of the rock may have been derived from a basic feldspar. It is clear, however, that the great mass can not owe its origin to this process, but must be the result of infiltration. The calcite grains derived from, and lying in, the feldspar acted as nuclei, around which the infiltrated calcite was gradually collected, producing pseudomorphs after the feldspar laths. Quite recently Dr. W. S. Bayley[1] has noted in the Clarksburg submarine volcanic formation of the Marquette district, Michigan, the occurrence of tuffs, in which calcite has been introduced in such quantity that they may almost be called limestones.

In another case in which the alteration of the ellipsoid (Pl. XI) apparently proceeded along the lines of shearing, and produced the kind of aggregates of chlorite, including crystals and aggregates of epidote-zoisite, which were described (p. 117) as the usual matrix of such ellipsoids, one can see in thin section the calcite entering the chlorite aggregate along minute fissure lines. The calcite literally eats its way into the chlorite, and produces by an interchange of elements a mass of calcite (magnesian ?) and epidote, besides including epidote which originally occurred scattered through the chlorite aggregate.

The carbonation of the original basalt or of the secondary chlorite mass results in producing a mass of carbonate which has associated with it some secondary quartz, chlorite, and epidote. This carbonate mass may be almost massive or it may be decidedly schistose. When schistose, the grains of calcite and quartz have a uniform elongation, and the schistosity is materially enhanced by flakes of chlorite, which are not uncommonly found in thin streamers or thick masses in the carbonate aggregate, at times in sufficient quantity to give it macroscopically a decided green tinge.

I have used the term "carbonate," although having described in detail above the calcification of the basalt, for the reason that at times, and for no

[1] Mon. U. S. Geol Survey, Vol. XXVIII, p. 473.

discernible reason, the iron carbonate (siderite) may replace the calcite, in which case we get a dark bluish-black variety of matrix (p. 117). The siderite masses do not differ essentially from the calcite, though in some of them a very small quantity of actinolite is found associated with the chlorite. As illustrating the purely local development of these two carbonates, I would mention having observed in one section a band of siderite separated from a band of carbonate, which from its color appeared to be quite pure calcite. One may also see commonly in exposures areas of pure white calcite, almost in juxtaposition with areas of siderite.

It is a fact generally recognized that carbonation is a process confined to the outer crust of the earth, so that we may perhaps best explain the local occurrence of these carbonates replacing the basalt as products of carbonate-bearing waters. That such carbonation of the igneous rocks through which these waters percolate is now taking place seems certain. The carbonate grains in the rocks described are shattered and elongated, or at least show undulatory extinction. They thus give evidence of having been more or less mashed since their production, and this mashing probably took place after they had been more or less deeply buried, and was, as a matter of fact, to some extent due to the pressure of the superincumbent rocks.

The probability that these rocks have been thus deeply buried subsequent to their formation is to be borne in mind with special reference to the next process to which they have been subjected, that of silicification. This process is most clearly shown in the siderites, and the phases of alteration noted in their study will be briefly described.

The microscope shows the siderite matrix to be a coarsely granular aggregate composed essentially of crushed siderite grains. Between these grains in a few places are small grains of quartz, flakes of chlorite, and very rarely needles of actinolite. Large quantities of black ferruginous specks are included in and also lie between the quartz grains, and such specks are also to be seen included in siderite areas, but close inspection shows that they are also associated with blebs of quartz. The chlorite flakes and quartz grains are generally elongated in the same direction, and the quartz shows wavy extinction.

A more advanced stage in the process of silicification was studied in the case of a rock which is bluish-black in color, exceedingly fine grained, and minutely schistose, the schistosity agreeing with the contours of the

ellipsoid from around which it was broken. This is essentially an exceedingly fine-grained quartz rock, with chlorite flakes and black ferruginous specks scattered through it, and here and there an irregular oval siderite grain remaining. Very few and unimportant grains of epidote were also noticed. This rock represents nearly the last stage in the process of silicification by which the siderite has been replaced, and a part, probably the greater part, of its iron content oxidized. Some chlorite and epidote has been produced, clearly from the lime and magnesian impurities in the siderite. Essentially the same process of silicification has been described by Van Hise in his various articles on the Penokee-Gogebic and Marquette iron ranges, to which references have been so frequently made. I have desired especially to call attention to it here, however, on account of the fact that it shows the possibility of the production of an iron ore from an original eruptive rock by the combined processes of carbonation and silicification. It is true that the end product in the case described does not contain enough iron to be an ore deposit, but that is a mere detail. May not this serve also to some extent to explain the numerous clearly marked belts of magnetic attraction which occur throughout this area of altered basalts, in which little of the original magnetite remains unaltered to exert an influence upon the magnetic needle? To explain this we must suppose the influence to be exerted by secondary magnetite accumulated along certain lines. The magnetic lines traced out agree in a very marked way with what has been determined to be the trend of the lava flows and tuff beds. The condition which would determine the presence of such a line of carbonation, if we may so put it, may be the presence of a scoriaceous lava flow or a bed of tuff, which offers exceptional facilities for the passage of carbonate-bearing waters. It is thus intimated that there is possibility of finding purely local ore bodies of small size even in the midst of this volcanic area.

The process of silicification is generally considered as a deep-seated one, occurring far below the outer weathering zone.

When the rocks exhibiting these various phases of silicification are exposed in the zone of weathering, certain interesting results are obtained which are worth noticing. Rocks are produced from these which upon the surface strongly resemble amygdaloids, but in which the pseudo-amygdaloidal cavities are of purely secondary origin. For instance, when the siderite mass has become only partially replaced by silica, weathering

agencies leach out the remaining siderite areas and leave the thin films of silica which lie between them standing up, thus giving the rock the appearance of a very dark pumice. As the silicification progresses the siderite is very much reduced in quantity, the intervening siliceous areas increasing correspondingly. The pressure exerted upon the rock has caused the isolated siderite areas to take on an oval character, the longer axes in general agreeing and being perpendicular to the pressure. When such siderite areas are leached out, the silica bands remain, and pseudo-amygdaloidal cavities are produced, giving a very perfect pseudo-amygdaloidal structure to the hand specimen. This is the origin of that character of matrix which some of the geologists have described in their field notes as like rotten, worm-eaten wood (fig. *B*, Pl. XXVII).

Although at present the material between the ellipsoids differs so markedly from the rock forming the ellipsoids themselves, nevertheless there is no reason for supposing the original composition of that part of the rock mass to have been essentially different. The change in the character of the basalt in passing from the ellipsoids toward the schistose matrix is in mineralogical character much as has been described for other basalts from this same district. The reason for the more complete degree of the replacement process in passing away from the ellipsoids may be readily understood from the discussion of the origin of the ellipsoidal parting of the basalts, where the conclusion was reached that the matrix between the ellipsoids resulted from the comminution of basaltic material of the same general character as that of the ellipsoids. This matrix was of course more porous and probably more vitreous than the basalt, and hence more liable to be altered.

PYROCLASTICS.

The majority of the clastic rocks have been derived from the basic volcanic rocks already described. These clastics are very characteristic of the Hemlock formation and constitute the greater part of it. They comprise several classes, the more important of which are the eruptive breccias, volcanic sedimentary rocks, and schistose pyroclastics.

ERUPTIVE BRECCIA.

The term "eruptive breccia" is here used to include those clastic rocks in which angular fragments of an igneous rock are surrounded by a matrix

also of igneous origin. In an eruptive breccia the fragments may be like or unlike. Likewise the matrix may be like or unlike the fragments. Where the fragments have been rounded during the movement of the eruptive magma surrounding them, the resulting rock may be called an *eruptive pseudo-conglomerate.*

Eruptive breccias are not very common in the Crystal Falls district. Where they do occur, the fragments, while predominantly angular, are to some extent more or less rounded, and are similar in nature to the matrix in which they lie. Since the rocks which form them preserve the main characters of the massive lava flows which have just been described, they will not be discussed in detail. The exact method of the formation of these breccias could not be told.

In one case, in which both fragments and matrix are amygdaloidal, it appears probable that the occurrence represents a true flow breccia in which the broken surface of a lava flow had been recemented by a later lava flow of the same kind of rock, or that it represents a very possible case in which the lava welled up through and flowed over portions of its own crust, cementing the fragments. In such breccias a flow structure around the fragments is quite plainly shown and the matrix possesses a peculiar ropy appearance. In one instance, in which both the fragments and matrix were macroscopically nonamygdaloidal, it is probable that they were formed under considerable pressure, and that this was a case in which lava was forced up through a previously consolidated mass of rock of like character, and in its passage carried with it various fragments, forming an *eruptive "reibungs-breccia"* or *friction breccia.*

VOLCANIC SEDIMENTARY ROCKS.

Under the term "tuffs" have been very generally included all kinds of volcanic clastic rocks.[1] This is probably due to the fact that there is frequently considerable difficulty in discriminating between eolian deposits and those which have been deposited in water. It seems desirable, wherever it is possible, to make this discrimination. To that end I shall in the following pages restrict the term "tuff" to eolian deposits. The term "volcanic conglomerate," or, for the sake of brevity, simply "conglomerate," will be used for those coarse deposits which have been sorted by and deposited

[1] Text-book of Geology, by Sir Archibald Geikie: 3d ed., p. 135.

in water, and whose fragments show a rounded character. Should the fragments be angular, the rocks may be called "volcanic breccias."

It has been found practicable to maintain this distinction in earlier studies on Tertiary volcanics,[1] and it is also maintained in the present study of pre-Cambrian volcanics. I am confident the same distinction could be made more generally than it is, and would in that case tend to a greater precision in the separation of rocks of different characters. However, it is rather difficult to separate true eolian deposits of volcanic fragmentary materials from those in which the fragments have been deposited rapidly through water without having embedded organic remains and without having undergone sufficient attrition to be much rounded. More or less rounding, it is well understood, results from the attrition of the volcanic ejectamenta during their ascent and descent through the air, so that they may in this respect resemble many of the sedimentaries. The exact mode of origin of many of the volcanic fragmental deposits of the Michigamme district is not clear. The greater portion appear to be of true eolian origin, and where the origin of any is in doubt it has been put with those of eolian origin.

COARSE TUFFS.

The coarse tuffs include rocks composed of fragments of all sizes, from the large volcanic blocks to the fine-grained particles of sand and dust which fill in the interstices. The ejectamenta may be more or less rounded by attrition during their progress through the air, so that if a refinement of the nomenclature should be needed one might very properly be justified in speaking of tuff breccias and tuff conglomerates.

Tuffs are very common and characteristic for the district. The characters of the beds is best shown on the weathered surfaces. Here the scoriaceous and dense light-green fragments stand out well from the brownish-red matrix of more altered, finer fragments and cement. On a fresh surface the interstitial material usually has a darker green color than the fragments. The fragments have a prevailing green color, but many, especially in sections, are brown, much darker than any of the rocks forming the lava flows. The larger fragments are usually sharply angular, but in many cases are more or less rounded because of attrition during

[1] Die Gesteine des Duppauer Gebirges in Nord-Böhmen, by J. Morgan Clements: Jahrbuch K.-k. geol. Reichsanstalt, Vol. XL, 1890, p. 324.

their progress through the air. (Pl. XIII.) They are for the most part not scoriaceous, though rather commonly amygdaloidal. The macroscopically dense fragments seem to predominate, though the amygdaloidal ones do occur in some specimens in nearly equal quantity.

The fragments of the tuffs are derived from the various kinds of basalt already described as forming the lava flows.

Among the fragments some of the most typical of these rocks have been found, and remarkable as it may seem, some of the thin sections from them show the least-altered basalts.

In addition to the kinds mentioned under the basalts there are a number which differ slightly from them, and apparently represent more glassy modifications of the basalt magma. In one of these the amygdules are more sharply outlined by the accumulation of iron oxide around the edges of the amygdule than is the case in the crystalline flow rocks. An especially well-preserved fragment shows perfectly fresh plagioclase microlites exhibiting well-developed fluidal structure lying in a dark-brown apparently isotropic glassy base. Where the section is thin, globulitic devitrification products can be seen, and there also the base no longer appears isotropic, but very feebly double refracting. There is very frequently found among these tuffs amygdaloidal fragments which appear to have been derived from what was originally a completely glassy rock, no indication of the presence of any original crystals having been preserved. The background of these fragments consists of a fine felt of a green chloritic mineral, dotted with innumerable grains of epidote, in which one may distinctly discern concentric circles and arcs of circles outlined by aggregates of epidote grains. These circles probably represent perlitic partings. (Fig. *A*, Pl. XXXII.) The dark-brown fragments mentioned as occurring with the prevailing green ones are very dense, appear to be very rich in iron, and may possibly represent a very basic devitrified glass. Should accumulations composed essentially of such glassy fragments be found, they could properly be called "palagonite tuffs."

In addition to the rock fragments, a few rare ones of large plagioclase crystals were found, and also in one case a fragment of a violet-brown augite, the only specimen of fresh pyroxene thus far found in any of the volcanics.

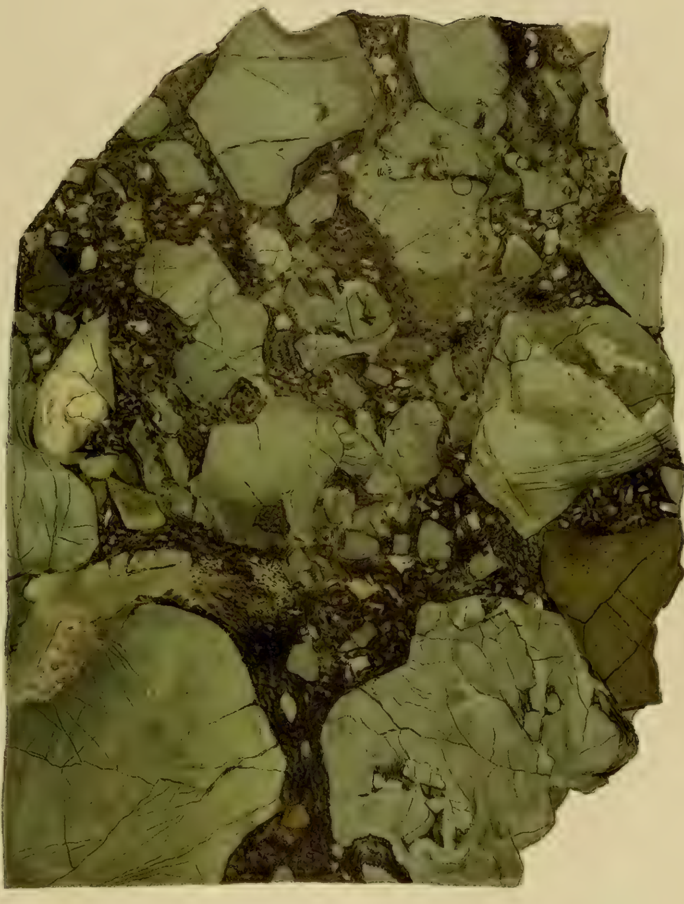
The tuffs show in places fairly well-developed banding, caused by the

PLATE XIII.

PLATE XIII.

(Sp. No. 23644. Natural size.)

This illustration is a faithful representation of the appearance of the polished surface of a pyroclastic from the Hemlock formation. It is somewhat doubtful whether or not the fragments composing the rock have been deposited through the mediation of water or air alone. The larger fragments are rather dense. Vesicular fragments are more common among the smaller particles. Pyroclastics similar in appearance to this are of very common occurrence in the Crystal Falls district, and huge cliffs of it are readily accessible from the railroad.



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BASALT TUFF.

interbedding of layers in which coarse and finer fragments prevail, illustrating well the varying intensity of the volcanic discharges.

Owing to the fragmental nature of the exposures, it is impossible to get a correct idea of the maximum thickness of any of the tuff deposits. Exposures were seen in the north half of sec. 5, T. 43 N., R. 32 W., which gave a thickness of over 500 feet for some of these deposits, but as their farther continuation had been cut off by valleys, most probably eroded in the tuffs, no means was afforded of determining their total thickness.

It is almost needless to state that the most of the tuffs have undergone a great amount of alteration. The alterations were apparently due to an interchange of the various elements without any essential variation in the chemical nature of the rock as a whole. Since water is the chief agent through which alterations occur, these always begin along the interstices. In the case of the fragments the alteration accordingly proceeds from the outside inward, and ordinarily at an equal rate all around the fragments, following its contours. In this way zones of somewhat different mineralogical composition are formed, surrounding the less altered part of the fragment. This secondary zonal structure may be observed more or less imperfectly in almost all of the sections made from the breccias, but is much better shown in the field, where the concentric zones are well brought out on the large weathered surfaces of the bowlders.

In each case the outside, lighter-colored zone is chiefly made up of chlorite, from which project light-green hornblende needles into the matrix beyond. Less commonly we find it composed of epidote grains and chlorite. Inside of this zone the mineral elements composing the fragments sometimes can not be determined with any great degree of certainty. Where determinable, the alteration products are found to be the same as are produced from the corresponding rocks in the lava flows. As also in the lava flows, some of the fragments of the denser rocks have become almost opaque from the quantity of minute secondary epidote and sphene grains. These have a lighter green color than the less altered fragments.

In examining many of the tuffs, one is repeatedly struck by the large amount of space occupied by the cementing material. In some cases cavities of very considerable size were left between the fragments. It appears that the fragments must have been lying very loosely. This fact tends to confirm the eolian origin of the rocks, since water deposition tends to bring

the fragments in close contact, and also to fill the intervening spaces with fine detritus. Those cases must of course be excepted where the material fell upon water so deep that after sinking to the bottom the action of the waves was not felt. Under such circumstances one can imagine the blocks, being partly supported by the water, coming to rest in a more unstable position than they would in the air.

The cement differs in different specimens. The minerals constituting it are quartz, feldspar, calcite, chlorite, epidote, and hornblende. The minerals are found including one another in such a way as to make it probable that they usually formed simultaneously. The calcite is an exception, as it is usually present in greater quantity near the surface of the exposures, and is therefore a weathering product. It was noted above that the hornblende and chlorite frequently extend from the rock fragments into the clearer elements composing the cement. Hornblende needles in many cases constitute a large part of the cement. Where two fragments are very close together, a perfect network of needles may extend from the one across the intervening space and penetrate the other, and the fragments thus practically grow together. The cavities—especially the large ones mentioned above—have quite frequently been filled with concentric growths of various minerals. In general, chlorite seems to be the first mineral deposited, and quartz the last, but in weathered specimens calcite is the last.

FINE TUFFS OR ASH (DUST) BEDS.

The fine tuffs or "ash" beds occur plentifully in the Crystal Falls district. In many cases they possess a very well developed cleavage, and were very puzzling in the field on account of their striking resemblance to true sedimentary slates. They are of interest as emphasizing the resemblance between pre-Cambrian ejectamenta and Tertiary and Recent ones. In one respect they differ from the modern forms. The dust from Krakatao in 1885 and from other volcanic explosions consists mainly of fragments of minerals and glass. The constituents of the Crystal Falls beds are usually fine lava and glass fragments and less commonly minerals.

The rock fragments are angular, vesicular, and completely altered. The glass fragments are likewise angular, and have the characteristic curved shapes from which they are usually described as sickle-shaped bodies. (Fig. *B*, Pl. XXXII.) Such are formed when a pumice is broken up, and each

represents a portion of the glass bounding the vesicles. Here and there is a fragment with a more or less perfect vesicle remaining. The few mineral fragments found—feldspar—were angular, but quite fresh. The rocks show no intermixture of rounded fragments, and they are consequently regarded as volcanic dust deposited through the air. These ash beds show a delicate banding of finer and coarser-grained fragments. In a single slide a gradation can be traced from a moderately fine grained sand composed of distinct volcanic fragments into a very fine grained mass composed of hornblende needles, biotite, chlorite, epidote, and sphene, cemented by what is probably quartz, perhaps having associated with it some feldspar whose characters could not be determined.

Relations of tuffs and ash (dust) beds.—The pyroclastics seem to predominate in the northwestern part of the district in the neighborhood of the small town of Amasa. Special opportunities for observing the relations between the tuff and the ash beds are offered by the third cut of the Chicago, Milwaukee and St. Paul Railway west of Balsam, Michigan. Gradation can be traced from coarse tuffs to delicately banded fine tuffs. The average thickness of a single ash bed probably does not exceed 5 feet. In the same exposures the tuff beds are from 50 to 100 feet thick, and even more.

VOLCANIC CONGLOMERATES (TUFFOGENE SEDIMENTS, REYER).

That certain of the pyroclastics have been brought together and rearranged by the agency of water is made clear by their characteristic structure. Such rocks are the volcanic conglomerates. In very many respects they are strikingly like the various eolian deposits, tuffs, etc., described above. They agree with them in color. The same varieties of volcanic rocks are represented that are found in the tuffs. They are true basalt conglomerates.

The pebbles are very commonly sharply outlined by accumulations of epidote grains on the periphery. Some of the fragments have a reddish-brown to purplish-black color, and stand out strongly from the green matrix. Such pebbles are found to contain large quantities of magnetite, the oxide being in beautiful sharp crystals and in absolutely fresh condition, forming a sharp contrast to the altered condition of the fragments in which it occurs. In one case in which the main mass of the fragments now consists of chlorite and epidote, magnetite occurs in large quantity,

and in chains of crystals forming dendritic growths. The oxide is clearly secondary in these altered rocks. Since it also occurs secondarily in the cement, it appears highly probable that it is an infiltration product formed during or after the metasomatic process.

In these conglomerates feldspar fragments are far more common than they are in the tuffs, and they show a well-defined, round, waterworn character. (Fig. *A*, Pl. XXXIII.) Likewise masses of uralite are commonly associated with the rounded feldspar. The uralite is taken to be altered pyroxene fragments, though no proof of this beyond its association could be offered, as the fragments show no characteristic pyroxene outlines. The well-rounded nature of the volcanic pebbles makes it certain that they have been deposited through the mediation of water and enables one easily to distinguish the typical examples in the field.

In size the fragments differ from one another just as they do in the case of the eolian deposits (fig. *B*, Pl. XXXIII). Many of the largest are several feet in diameter, but more commonly they vary from a couple of feet in diameter to small pebbles. Partly filling the interspaces and aiding in cementing the larger fragments, with which they are associated, are very fine grained fragments derived from the trituration of the waterworn lapilli and blocks. The coarse bowlder conglomerates grade through finer conglomerates into very fine material. This fine material shows beautifully marked false bedding. (Fig. *C*, Pl. XXVII.)

In one of the finer-grained rocks, in addition to the usual sedimentary banding, there are bands which appear to have been caused by a further sorting of the materials, some of these bands being composed almost exclusively of uralite. They consequently represent bands which were originally composed mainly of pyroxene fragments. In this case, when the fine ejectamenta settled through the water they were separated according to size of grain and specific gravity, as in ore-dressing processes.

Under the microscope other points of difference in addition to those above mentioned are noted between the conglomerates and the tuffs or eolian deposits. The fine-grained rocks corresponding nearly to the volcanic sand, do not consist of distinguishable rock fragments, but of clearly rounded feldspar grains which have been enlarged by peripheral additions of feldspar substance, bunches of uralite, some chlorite, and of sphene secondary after titanic iron. The photomicrograph, Fig. *A*, Pl. XXXIII,

illustrates the appearance of the thin section of such consolidated sand, which possesses in no place the structure of an igneous rock, and which, moreover, grades into a finely banded rock composed of minute needles of hornblende, chlorite, and grains of epidote, lying in a clear minutely crystalline groundmass of quartz or of feldspar, or possibly of both.

The finer material cementing the recognizable fragments is the same as it is in the tuffs. The large bowlders and pebbles lie in a matrix of smaller pebbles, and these in turn lie close together in a paste which has been completely altered, and does not in all cases show clastic characters. The cement is composed of hornblende, chlorite, sericite, epidote, feldspar, and quartz, and in one case large porphyritic rhombs of a ferruginous carbonate are scattered through the finer-grained material of the cement.

In the cement of the tuffs hornblende is present in large quantity and feldspar is not so abundant. In the cement of the conglomerates feldspar seems to be rather plentiful, hornblende is present in a comparatively small quantity, and chlorite is more abundant, thus reversing the order of these minerals in the conglomerates.

SCHISTOSE PYROCLASTICS.

At various places in the Hemlock formation there occur clastic rocks which have become schistose. Two isolated exposures of pyroclastics are known whose characteristics have been so changed that, while recognizable as clastics, it is impossible to say whether they belong to the eolian or the water-deposited class. Upon weathered surface the rock is covered with brownish ochre, and on fresh fracture it is dark green and very schistose. Neither in exposures nor in hand specimens does it give any indication of its origin.

In thin section, however, one may see macroscopically the fragmental characters. The fragments are elongated and rounded. The amygdaloidal texture is also seen, showing the volcanic nature of the fragments, though the majority of the fragments are dense. Under the microscope the fragmental nature of the rocks as a whole and the volcanic character of the fragments forming it are still more clearly seen. In the centers the fragments are seen to be composed of chlorite flakes in such great quantity as partly to conceal the character of the clear white cement, which is supposed to consist for the most part of quartz, though lath-shaped areas with poly-

synthetic twinning, showing the presence of plagioclastic feldspar, were seen in places on the edge of the section. In the chlorite and quartz occur large grains of fresh titaniferous iron ore, altering on edge to sphene, and, most striking of all, large porphyritic, beautifully automorphic calcite rhombs and muscovite plates in isolated individuals as well as in heaps of crystals. The carbonate, which predominates, effervesces readily with cold HCl, but is evidently ferruginous as it is yellowish when altered, and from it results some of the ochre which colors the weathered surface of the rock. In other sections the calcite phenocrysts are scalenohedra, with very few rhombohedra. The terminal faces are not sharply defined. The sections resulting from the scalenohedra are long, lath-shaped, and have pointed or irregular ends, parallel extinction, and oblique cleavage.

In passing from the centers toward the edges of the fragments, we note a marked diminution in the amount of carbonate, muscovite, chlorite, and iron oxide, causing a consequent lightening in color of the periphery. This gives the zonal structure noticeable upon the macroscopical examination of the thin section. The schistose character of the fragments is caused by the parallelism of the chlorite flakes.

The cement between the fragments is composed of quartz in rather coarse grains, chlorite in larger flakes than in the fragments, and carbonate in large porphyritic crystals, and also in minute rhombs included in the quartz grains. Another phase contains considerable secondary plagioclastic feldspar associated with the quartz in the coarser-grained portion of the cement. As in some of the conglomerates and tuffs, the fragments are observed lying in juxtaposition, the only cement between them being the secondary interpenetrating minerals. In some cases the edges of the fragments have been so welded that one may pass from one pebble to the adjoining one across an intervening lighter zone without detecting the transition, unless changes in the amount of chlorite, iron oxide, and carbonate are noticed.

Nothing thus far mentioned would indicate the igneous origin of the fragments, but that is indisputably proven by the amygdaloidal texture of the specimens, than which I have seen none better, even in the freshest volcanics. The outline of the cavities is marked by an accumulation of grains of iron oxide, and the cavities themselves are filled by fine-grained quartz having a small amount of chlorite associated with it. (Figs. *A* and *B*,

Pl. XXX.) These specimens have the characters of the porphyritic schistose lavas described above, but show clearly that they have been derived from igneous clastic rocks.

Other schistose clastics occur in large quantities in sec. 24, T. 46 N., R. 33 W. They are penetrated by a boss of coarse poikilitic dolerite which may have aided in rendering them schistose, though their schistosity agrees with the general strike of that of the rest of the district, and is probably chiefly due to the general folding.

Macroscopically their clastic structure may be clearly seen. The pebbles are dense greenish gray in color and oval in outline. The matrix is a much darker green. The schistosity of the rock is marked. The pebbles are uniformly elongated, and they have the appearance of having been mashed. The schistosity agrees in direction with the elongation of the pebbles.

The microscope shows the pebbles to be basaltic, with a type of structure intermediate between the navitic and intersertal structures, and another with approach to the trachytic structure. Considerable brown mica is present in both kinds, and occurs in flakes which are probably secondary, though the pebbles show few traces of alteration. The matrix consists essentially of actinolite in rather coarse needles, large grains of fresh magnetite, but very little mica, and that such as is seen in the pebbles, all lying in a cement of quartz and calcite. The passage between the cement and the pebbles is a more or less gradual one, there being a change as we pass from the center of the pebble, where isolated actinolite needles and epidote grains occur, toward the edge, where these minerals increase in amount until between them here and there are twinned feldspars. In the matrix proper the quartz is the predominant white silicate, though here and there limpid feldspar is also seen. The pebbles are gradually being eaten up, so to speak, by the actinolite, and we can imagine the final result to be an actinolite-schist showing no clastic structure, and giving absolutely no indication as to the rock from which it originated.

There is no microscopical evidence of mashing in the minerals, and since this is absent from the quartz in the cement, I conclude that no original clastic cement is now present, and that the quartz is a secondary crystallization product derived from infiltrated material and from material obtained from the adjacent pebbles. Whether the rock is an eolian deposit or a

waterworn sediment can not now be definitely determined, though that it belongs to the first appears more probable.

Still another rock very similar in general character but differing in detail, and showing a slightly different result, has been examined. The pebbles are basalt, and in them the secondary nature of the biotite, which has chlorite associated with it, is clearly shown. Near the centers of the pebbles very little is present, but it rapidly increases in amount toward the periphery, until at the edge only here and there the feldspars may be seen between the mica and chlorite flakes. The cement between the pebbles consists of angular fragments of altered orthoclase feldspar, quartz, and a great quantity of chlorite, and some biotite. This cement is present in large quantity.

In both of these last the secondary minerals are parallel, and produce rocks of most decided schistose character. These schistose pyroclastics may be compared with the rocks described by Williams[1] and Bayley[2] from the related rocks in the adjoining Marquette district.

THE BONE LAKE CRYSTALLINE SCHISTS.

Under this name are included certain crystalline schists which are best developed in the northern part of the Crystal Falls district, in the vicinity of Bone Lake. If one examined isolated specimens of certain of these rocks, it would be impossible to determine their origin. Studied in connection with the alteration of the altered and schistose lavas and pyroclastics already described, the problem becomes greatly simplified. These schists, as will be shown on the following pages, are but extremely metamorphosed members of the Hemlock volcanic formation. Since in the limited area in which the rocks occur the secondary characters are dominant, while the primary volcanic characters have nearly all disappeared, a brief separate description of these rocks seems warranted, but they are not represented by a separate symbol on the map.

DISTRIBUTION.

The crystalline schists predominate in T. 46 N., R. 32 W. Near the western limit of this township the belt occupied by these rocks is about 2 miles wide. As it is followed to the east past Bone Lake, and then to the

[1] Bull. U. S. Geol. Survey, No. 62, cit., pp. 185–191.
[2] Mon. U. S. Geol. Survey, Vol. XXVIII, cit., pp. 160–169.

southeast, it gradually narrows, until in sec. 36, T. 46 N., R. 32 W., the eastern limit of the area studied by me, it is only about half a mile wide. Except in the vicinity of Bone Lake, where erosion has uncovered some of the knobs, outcrops are very scarce, since the drift is very heavy, and the drainage is poorly developed.

FIELD EVIDENCE OF CONNECTION WITH THE VOLCANICS.

If one examines attentively the Hemlock formation in its typical development, beginning, say, in sec. 27, T. 45 N., R. 33 W., and following its northward extension through secs. 22, 16, and 15 of the same township, he will observe instances of banding in the tuffs and of schistosity in the amygdaloidal lavas and pyroclastics. The strikes and dips of the primary and secondary structures approximately coincide, both having a general north-south strike and dipping high to the west. Throughout this area, however, the unmistakable massive volcanics are the predominant rocks. Continuing the examination farther north into sec. 34, T. 46 N., R. 33 W., rocks are found which possess almost invariably a strongly marked schistosity, but with their volcanic origin clearly shown by the flattened amygdules. This is also true for the exposures east of this place on the under side of the Hemlock belt, in sec. 31, T. 46 N., R. 32 W. The strike of the schistosity of the amygdaloids varies from N. 30° to 70° E., and the dip is high to the northwest. Farther along this belt to the northeast, in sec. 24, T. 46 N., R. 33 W., schistose pyroclastics were observed striking N. 80° E. The original characters of these pyroclastics have been almost entirely obliterated. The exposures next to the east in sec. 16, T. 46 N., R. 32 W., possess all the characters of crystalline schists. Somewhat farther east, however, associated with these schists are isolated outcrops in which traces of flow structure and remnants of amygdules were observed, and, in some, traces of igneous textures were seen under the microscope. The schistosity of these rocks strikes for the most part south of east, varying from N. 65° to 80° W. and dipping to the northeast. Following the belt as it now turns to the southeast, the crystalline schist characters prevail, the volcanic characters being obliterated. The schistosity at the same time bends farther around to the southeast, pointing toward the continuation of this area of volcanics to the southeast, outside of the area studied.

From field observations the conclusion seems necessary that these

schists are metamorphosed volcanic rocks, and this conclusion is strengthened by detailed petrographical examination.

PETROGRAPHICAL CHARACTERS.

The crystalline schists are fine to medium grained schistose rocks which vary in color from a moderately light green for the more chloritic phases to a very dark green and purplish-black for those in which the hornblende, mica, and iron ores are prominent. The minerals of which the rocks are composed, arranged in order of importance, are hornblende, biotite, feldspar, chlorite, epidote muscovite, quartz, magnetite, hematite, ilmenite, and rutile. Under the microscope the schistose structure is seen to be produced by the general parallelism of the bisilicate constituents. The porphyritic texture is seen in a few specimens, and hornblende forms the phenocrysts.

Hornblende occurs in fine needles and also in coarse crystals which are automorphic in the prismatic zone, but on which no terminations have been observed. It also occurs rather commonly in sheaf-like bundles of ragged crystals. The marked orthopinacoidal development so common for actinolite is quite noticeable. The crystals show the usual strong pleochroism: $\mathfrak{c}$=bluish-green, $\mathfrak{b}$=olive green, $\mathfrak{a}$=yellow, whereby $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$. The hornblende crystals frequently contain large quantities of the minerals of the groundmass, many of them in such quantity that there are really only skeleton hornblende crystals present. The general character of the hornblende in all these rocks is that of a secondary porphyritic constituent, and seems to be analogous to such minerals as garnet, staurolite, etc., which are produced in clearly metamorphic rocks.

Brown biotite is rather common in some of the rocks. Though usually subordinate to the hornblende, it is at times the predominate bisilicate. It is light brown and shows the usual characters of biotite. It is present in small irregular flakes, and also in larger individuals which show poor pinacoidal development. In one case such a mica individual in perfectly fresh condition may be seen with its ragged edges interlocking with the fringed periphery of an altering feldspar crystal. The biotite appears to have derived some of its necessary elements from the feldspar and to be eating into it, and consequently to be a secondary product.

Feldspar is not found as an original mineral in any of the crystalline

schists. It occurs as a secondary constituent. It is found, however, as a primary constituent in a few rocks which, as they still possess remnants of original igneous textures, strictly speaking, should not perhaps be included with the crystalline schists. They represent more properly the transition stages to the crystalline schists, but the process of the alteration of the feldspar is so well shown in these that it is considered expedient to mention it at this place. The original feldspar occurs in this transition phase in the large tangled intergrowths commonly seen in andesitic and basaltic rocks, as individual phenocrysts, and as microlitic lath-shaped individuals in the groundmass. The greatest interest centers in the phenocrysts, as in them the changes which take place are more clearly seen. The feldspar phenocrysts are always cloudy, due to numberless black ferruginous inclusions. They also inclose the various secondary dark silicates composing the groundmass, grains of epidote, flakes of biotite, and crystals of hornblende. These are usually surrounded by very narrow clear zones, apparently feldspar. Near the edges of such altered crystals, and especially in the more altered individuals, these inclusions are more numerous, and are accompanied by grains of quartz and new feldspar (albite ?). These last two have certainly been derived from the alteration of the feldspar, but that mineral may possibly also have contributed something to the production of the dark silicates.

The secondary feldspar, that of the schists proper, is found in grains usually unstriated, though in a few cases striations were observed. This feldspar was not determined, but is probably albite The chlorite is in flakes scattered through the schists, showing the usual characters.

Epidote, muscovite, quartz, and rutile appear as usual.

Ilmenite is present in one case as micaceous titanic iron oxide, and is then in extremely thin plates which show a beautiful hexagonal development, though more frequently the plates are rounded. They are transparent with the characteristic clove-brown color. The thicker plates are thin enough to be transparent only along the edges.

The iron oxides, magnetite, and hematite occur in some of these rocks in large quantity. In certain parts of the area underlain by these schists considerable excavations have been made in search of iron, the presence of which was indicated by the magnetic needle, and moderately large bodies of ore have been found, though in no case in sufficient quantity to

admit of successful mining. Such ore bodies probably owe their presence in great part to processes active subsequent to the formation of the schists. (See p. 134.)

According to the quantity and association of the minerals described above as occurring in the schists, the following rocks may result from the complete metamorphism of the basic volcanics: Amphibolites, chlorite-schists, epidote-schists, mica-schists, mica-gneisses, and possibly siliceous hematite and magnetite ore. The complete metamorphism of dense basic lava flows into crystalline schists has been described by Williams[1] for the Menominee and Marquette districts, and also by Van Hise and Bayley[2] for the Marquette district. Williams[3] has also described the production of schists from the igneous clastics in the Menominee district and similar products have been described from the Marquette district both by Williams[4] and by Bayley.[5]

The above-described schists cover a considerable area, with only isolated exposures of rocks associated with them in which volcanic characters are recognizable. They are confidently believed to represent extremely metamorphosed volcanics of the same general original character as those constituting the Hemlock formation and belonging to the same relative period of extrusion.

The same conclusions have been reached by Smyth for similar schists along the Fence River to the southeast of those described. It is noticeable that the most intense metamorphism of the volcanics has taken place in the northern and northeastern part of the Crystal Falls district, that part in which the crystalline schists have been produced, though the explanation for this can not be offered.

NORMAL SEDIMENTARIES OF THE HEMLOCK FORMATION.

The normal sedimentaries are in small quantity. It has been seen (pp. 64, 78) that the Mansfield slate is overlain by a conglomerate in which volcanic material predominates, but which contains partly rounded fragments of chert and slate and round quartz grains derived from the underlying sedimentaries. But for the intermingling of this normal clastic débris

[1] Bull. U. S. Geol. Survey No. 62, cit.
[2] Mon. U. S. Geol. Survey, Vol. XXVIII, cit., pp. 152–159.
[3] Op. cit., p. 133.
[4] Op. cit., p. 158.
[5] Op. cit., pp. 160–169.

with the pyroclastics, the conglomerate shows nothing different from the volcanic conglomerate already described. It is a transition rock between the tuffs and the normal sedimentaries.

Similarly, in sec. 34, T. 45 N., R. 33 W., a gradation occurs in the upper horizon of the Hemlock formation from the volcanic conglomerates to the true normal sediments. The sediments are slates about 175 feet thick, containing lenticular masses of limestone. These beds dip 80° to the west, generally strike north, but vary in places a few degrees to the west. They are underlain by conglomerates containing well-rounded volcanic pebbles. This volcanic conglomerate grades from the coarse conglomerate up into what might be termed a water-deposited volcanic sand. The pebbles are all of volcanic material. Between the conglomerates and slates is a small area without outcrop. Overlying the slates is a succession of tuffs and lava flows.

The slates in color range from light gray and green to purplish red, and the lenses of limestone vary from cream color to purplish red. In thin section the slates are seen to be composed of a felt of sericite, chlorite, and quartz, with associated innumerable minute rutile crystals, and here and there a large spot of limpid quartz. A ferruginous carbonate is present in all of them in porphyritic rhombs. Where chlorite is abundant, the slates are a light green. Where iron oxide is abundant and the chlorite less plentiful, the slates are purplish.

The lenses of limestone are rather pure, consisting mainly of calcite, with some few scattered areas of cherty silica. On the edges of the lenses some of the slate material is found forming bands in the carbonate. These intermediate phases grade on the one hand into the pure carbonate, and on the other hand into the slate beds. From the crust of limonite, which may be seen on the weathered surface of the rock, the calcite is evidently rather ferruginous. The process of alteration is clearly seen under the microscope, where many of the grains are surrounded by rims of hydrated oxide of iron and hematite.

ECONOMIC PRODUCTS.

BUILDING AND ORNAMENTAL STONES.

The rocks of the Hemlock formation are not likely to be much used for building purposes. The compact basalts possess in a high degree the

two essential features of strength and durability. For trimming in contrast with lighter stones they might be found desirable, and it may be suggested that they are especially suitable for mosaics in which rich greens are desired. They are of too somber a color to be used in large quantity for anything else than foundations. Moreover, the difficulty and consequent expense of quarrying them, and their remoteness from cities of large size, will operate strongly against their use.

The pyroclastics are natural mosaics, and some of them have a very pleasing appearance (Pl. XIII) and are suitable for table tops, wainscoting, etc.

ROAD MATERIALS.

The importance of good roads in aiding in the material development of a region can hardly be overestimated, and in the building of good roads, especially in thinly inhabited regions, the proximity of good road material is of prime importance.

Thus far the 15 miles of good road between Crystal Falls and the adjacent mining villages have been covered with the ferruginous chert and slates from the dumps of the mines, and unroll themselves to the traveler like red ribbons laid through the green woods.

No rock is better suited for use in building macadamized roads than the basalt, and of this the Hemlock formation offers an inexhaustible supply. The fine-grained compact basalts are by far the best rocks obtainable, and, other things being equal, should of course be chosen rather than the scoriaceous and consequently weaker facies, but these weaker kinds and also the pyroclastics are preferable to the cherts and slates which have been used. The cherts are very hard and durable, but the dust and sand from them possess but slight capacity for cementation. Consequently the roadways upon which quartzite and chert have been used are more likely to wash out than are the roads macadamized with basalt, since the dust in this latter case serves as a cement which binds the larger fragments more firmly together. The road commissioners have thus far used very little basalt, chiefly for the reasons that no crusher was at their disposal, and the chert and slates were at hand ready for use.

CHAPTER V.

THE UPPER HURONIAN SERIES.

The upper series of this district is connected in the northeastern part of the area with the Upper Marquette series of the Marquette district already described in the Fifteenth Annual Report and Monograph XXVIII. In these reports the Upper Marquette series is regarded as part of the Upper Huronian. As has been stated, the Crystal Falls district is the southwestern extension of the Marquette district, and consequently we should expect the chief formations of the two districts to be continuous, as they are. Because of the drift and because of a change in the character of the rocks, in mapping the western part of the Crystal Falls district it has not been practicable to divide the Upper Huronian into several formations, corresponding to those in the Marquette district. No independent name will be given to it, but it will simply be called Upper Huronian, with the understanding that it corresponds stratigraphically to the Upper Marquette series.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Beginning in the northeastern part of the area discussed by me (see Pl. III), this series covers the southern parts of T. 46 N., Rs. 31 and 32, where it is only 4 miles in width. It is here a northwest-southeast syncline. From this place it stretches beyond the northern limit of the map. With slight interruptions where intrusives occur, it extends in a broad area to the west and south about the Hemlock volcanics to a point lying beyond the limit of the map. On the eastern side of the district it abuts against and is folded in synclines in the Archean granite.

Exposures are scanty for the greater part of the area in the Crystal Falls district underlain by the Upper Huronian series. This is due to two conditions, first, to the soft character of the rocks constituting the series, and, second, to the presence in places of the Cambrian sandstone, and more especially to the deep covering of glacial drift which is found spread over the entire district. The Upper Huronian is composed in great measure of

slates, which are interbedded with much smaller quantities of graywackes and chert. The slates are eroded much more readily than the associated harder beds, and therefore, except along valleys, we rarely find the soft slates exposed. The graywackes and cherty rocks are the ones which form the striking topographical features of the landscape, the slates forming softly-rounded hills. The drift is also an important factor in the scarcity of outcrops. In the northern and western parts of the districts especially the drift is very heavy. In this portion the youthfulness of the topography is emphasized by numerous swamps, lakes, and generally imperfect drainage. In the southern and southwestern parts of the district, owing to the presence of larger streams, and consequently more advanced erosion, the drift has been removed to a greater or less extent, so that the topographical forms approach much nearer to those of an unglaciated region. For instance, the general strike of the graywacke and cherty ferruginous slate beds in the southern portion of the area, T. 42 N., Rs. 32 and 33 W., can be closely followed by the north-south to northwest-southeast ridges which they form, the intervening valleys being in all probability underlain by the softer carbonaceous clay slates. Also in this vicinity, from the Chicago and Northwestern Railway eastward to the Michigamme River, exposures of intrusives with some sedimentaries stand out from the sand plains as rounded knobs.

MAGNETIC LINES.

A considerable amount of detail magnetic work has been done in the vicinity of the ore-bearing areas, in the hope that with the assistance afforded by the magnetic needle the iron belts might be better traced than they could be by means of the very scanty outcrops. I shall here describe those lines of magnetic disturbance which have been traced for considerable distances. They are indicated on the map, Pl. III, by solid blue lines.

Magnetic line D.—This line of maximum magnetic disturbance was traced northwest from near the southeast corner of T. 46 N., R. 32 W., around Bone Lake, then southwest and south through T. 46 N., R. 33 W., until finally lost near the south side of sec. 34 of the same township. The tracing of this line was begun where outcrops were wanting, and it was not possible to connect it directly with any magnetic formation until sec. 34, T. 46 N., R. 33 W., was reached. Here it was connected with outcrops of magnetitic slate and graywacke which overlie the Hemlock formation,

but with no contact exposed. Throughout its extent the line of disturbance is separated from the line of outcrops of the Hemlock volcanics by a short interval. It is, however, always distinctly separated from them.

Magnetic line E.—This magnetic line passes directly through the open pits at the Hemlock. As the line is traced north from this point it passes just west of an amygdaloidal lava one-half mile north of the mine. From this point until it is lost in sec. 16, T. 45 N., R. 33 W., there is no evidence in regard to the nature of the rock causing the attraction. Tracing the line south from the Hemlock mine it is found to swing about 200 paces east of the Michigan mine, near the north line of sec. 9, T. 45 N., R. 33 W. A quarter of a mile farther south it swings back again, apparently in the line of the continuation of the iron-bearing formation, which it follows for one-half mile farther, where it is lost. The only place along this line where it has been possible to determine the rock causing the attraction is at the Hemlock mine. Here it was found that it is not the ore formation proper which is magnetic, but that it is the foot wall. This is a magnetitic slate, about 42 feet in thickness, as shown by the diamond-drill borings.

The above are the only lines of maximum magnetic disturbance of this part of the Crystal Falls district which it has been found possible to connect in any way closely with the iron-bearing rocks. A large number of lines of disturbance, however, were traced within the limits of the Hemlock formation, but on account of their slight economic importance they are not inserted on the map. In these cases the influence on the needle is evidently exerted by the magnetite of the lavas and pyroclastics, and in proof of this the lines can very commonly be connected with exposures of the various volcanic rocks. It is of interest to note that the trend of the lines in the volcanics invariably agrees with that of the tuff beds, and with the general strike of the formations of the district, and the reader is reminded of the suggestion already offered (p. 134) that they may be caused by magnetite accumulated by secondary processes, especially active in the tuff beds and scoriaceous portions of the lava flows.

THICKNESS.

Since the Upper Huronian sediments cover a broad area, their thickness must be very considerable. Owing, however, to the scarcity of exposures, it is impossible to give even an approximate estimate.

FOLDING.

The extreme northwestern part of the area has not been studied in such detail as to enable the minor folds to be determined. In general, the series may be said to fold around the Lower Huronian, following the general outline indicated by its color, as shown on Pl. III, and having a steep dip away from it. In sec. 20, T. 45 N., R. 33 W., large outcrops of chert are folded in a most complicated fashion and are locally brecciated. South from this point the evidence of subordinate cross folds is marked. As a result, the line between the Lower Huronian and Upper Huronian is undulatory. The indentations in the Lower Huronian represent minor cross synclines, and the protuberances represent minor cross anticlines.

CRYSTAL FALLS SYNCLINE.

Near Crystal Falls is the most important of these synclines. This town and a number of small outlying mining villages are situated on a syncline. The character of this syncline is shown better by the distribution of the Hemlock volcanics than by the sedimentaries, owing to the scarcity of the outcrops of the latter (Pls. XVII and XVIII). The broad belt of northwest-southeast trending volcanics, situated 3 miles northeast of Crystal Falls, bends in secs. 11, 12, and 13, T. 43 N., R. 32 W., to the south, and gradually changes to a slight southwest trend. In the reentrant angle of this volcanic formation is the Crystal Falls syncline, its course being that of a southwestward-opening U. The axial line of this U probably has a westward pitch, corresponding with the general folding of this part of the district.

Near the center of the U and just a little northwest of Crystal Falls, in secs. 17 and 20, T. 43 N., R. 32 W., is an area underlain by volcanics, which trends east and west, and can be followed westward into sec. 1, T. 43, R. 35, beyond the limits of the area represented on the map. It varies in width from one-fourth mile to 4 miles, averaging about 2 miles. The contacts of these volcanics with the overlying Upper Huronian sediments are not exposed. Hence definite proofs of their interrelations can not be given. The volcanics have been folded with the sediments, and subsequent erosion has exposed them along the axis of an anticline.

The southern arm of the curved syncline bends around the extreme southern projection of the Hemlock volcanics in secs. 1 and 2, T. 42 N., R.

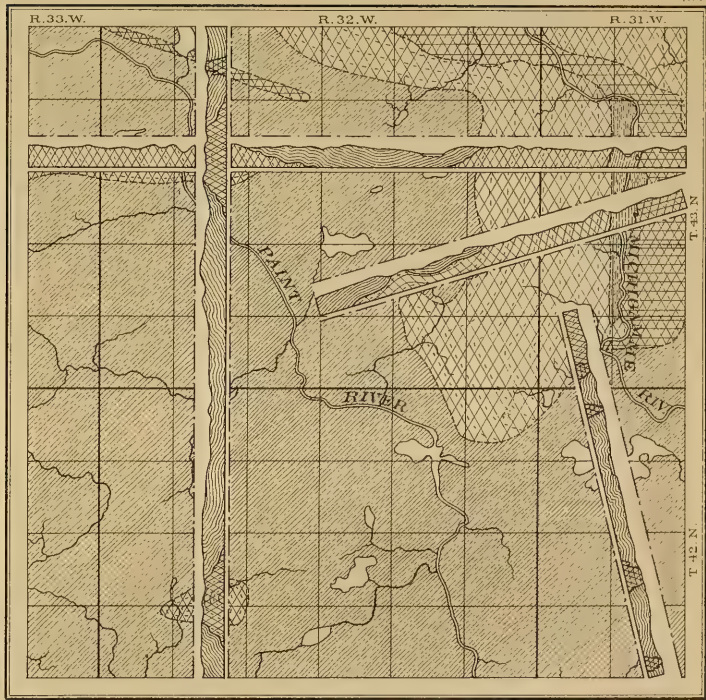
PLATE XIV.

PLATE XIV.

IDEALIZED STRUCTURAL MAP AND DETAIL GEOLOGICAL MAP, WITH SECTIONS, TO SHOW THE DISTRIBUTION AND STRUCTURE OF THE HURONIAN ROCKS IN THE VICINITY OF CRYSTAL FALLS, MICHIGAN.

Idealized structural map of the vicinity of Crystal Falls. An attempt has been made to illustrate upon this map the distribution of the Huronian rocks, and at the same time our conception of the general features of the structure of this area. The drainage is merely introduced for the purpose of orientation. The topography as here represented does not agree with the true topography of the area. The bottom of the geological basin now occupies, as the result of erosion, the highest places topographically.

Detail geological map, with sections, to show the distribution and structure of the Huronian rocks in the immediate vicinity of Crystal Falls. This serves as a key to the accompanying idealized structural map.



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IDEAL STRUCTURAL MAP AND DETAILED GEOLOGICAL MAP WITH SECTIONS TO SHOW THE DISTRIBUTION AND STRUCTURE OF THE HURONIAN ROCKS IN THE VICINITY OF CRYSTAL FALLS, MICHIGAN

VERTICAL SCALE OF SECTIONS - 1 INCH = 1200 FEET. ELEVATIONS OF BASE LINES = 1000 FEET ABOVE MEAN SEA LEVEL

SCALE 0 1 2 MILES

ALGONKIAN

LOWER HURONIAN: MANSFIELD SLATE; HEMLOCK FORMATION

UPPER HURONIAN: UNDIVIDED

INTRUSIVE: DOLERITE

31 W., and swings east north of Lake Mary into sec. 32, T. 43 N., R. 31 W. Here ferruginous slates are exposed, bordering the Michigamme River at the so-called Glidden exploration. The extension of these lowermost Upper Huronian beds east from this point soon passes under the sand plains and drift hills and is lost. The higher beds of the series are, however, exposed in the lower course of the Michigamme, Paint, and Brule rivers, which give good sections across them. In this portion of the area discussed the extension of even these higher parts of the formation can not, however, be followed farther east than the Michigamme River.

That the Crystal Falls synclinal basin is not simple, but has minor rolls, is shown by the way in which the Upper Huronian series indents the Lower Huronian at the eastern end. Also the close and complicated folding is shown by mining work, and can be nicely seen in the open pits of the Columbia and Crystal Falls mines, in the exposures in the railroad cut near the Crystal Falls mine, and also along both banks of the Paint River near the town of Crystal Falls. Pl. XIV shows the general character of this syncline. The folding has produced extensive "reibungs-breccias." Near Crystal Falls, along the river bank, about one-fourth mile south of the railroad bridge, may be seen such a breccia, which has been formed at the junction of a chert with the slates.

TIME OF FOLDING OF THE UPPER HURONIAN.

The latest folding to which the rock of the Crystal Falls district has been subjected is that which affected the Upper Huronian and likewise involved the underlying Archean and Lower Huronian rocks. Therefore the determination of this period of folding is of especial interest, as marking the close of orogenic movements in this district.

Overlying the Upper Huronian is the Potsdam Cambrian, or Lake Superior sandstone. The beds of this formation are horizontal, or else show a very slight tilting, following the general inclination of the district, which perhaps to a great extent may be explained by the initial dips of the beds. They overlie with strong unconformity the upturned and strongly plicated beds of the Upper Huronian. This unconformity marks a lapse of time represented in other districts by the following events: (1) A period of upheaval and denudation of the Upper Huronian; (2) the subsidence and deposition upon the truncated Upper Huronian sediments of the hetero-

geneous volcanic and sedimentary Keweenawan series; (3) the upheaval and truncation of the Keweenawan, in which movement of course the Upper Huronian in the Keweenawan areas was likewise involved. Subsidence of the land areas and the transgression of the Cambrian sea followed, with deposition of the horizontal Lake Superior sandstone upon the inclined Keweenawan and Upper Huronian rocks. The Upper Huronian of the Crystal Falls district may have been involved in one or both of the foldings which took place prior and subsequent to the Keweenawan; or, second, since no Keweenawan deposits are known in the Crystal Falls district, it may be that it suffered an early period of powerful orogenic movement, which raised the rocks above the sea, and was synchronous with the pre-Keweenawan upheaval. A long period of erosion, accompanied perhaps by other less important orogenic movements, may have followed contemporaneous with the activity of the Keweenawan volcanoes and the oscillatory movements of the Keweenawan region. The latter I conceive to be the more probable view. If this is correct, the intense folding of the Upper Huronian sediments in the Crystal Falls district took place immediately preceding the deposition of the Keweenawan series in other parts of the Lake Superior region.

RELATIONS TO OTHER SERIES.

It has been seen that in the western part of the district the Hemlock volcanics are the highest member of the Lower Huronian. At the end of the volcanic activity there must have taken place a very general transgression of the sea, as is evidenced by the continuous belt of sedimentary rocks which encircle the volcanics. The very marked change in the character of the rocks from subaerial volcanics to true sedimentaries partly marks the division of the Upper Huronian and Lower Huronian series. The determining points in favor of this subdivision are found in the eastern part of the district described by Smyth, and in the Marquette district still farther northeast. In only one place in the western part of the Crystal Falls district, in sec. 26, T. 44 N., R. 33 W., has a contact between the two series been obtained. A drill hole here passed through a mottled slate just before entering the Lower Huronian volcanics. A similar slate was obtained at Amasa overlying conglomeratic volcanic material, which outcrops at the surface, but no direct contact has been found. With most careful examination I have been unable to determine whether the conglomeratic rock is a true volcanic

tuff deposited upon the land, or is water-deposited volcanic material, and thus possibly a basal conglomerate of the Upper Huronian.

In sec. 34, T. 46 N., R. 33 W., the Lower Huronian and Upper Huronian are found in very close proximity. Here the Upper Huronian is a ferruginous graywacke and is separated by only about 10 yards from the schistose volcanics. In this case careful search failed to reveal the intermediate rock. In only one case in addition to the Amasa instance has a distinct conglomerate been found which can be considered as a possible basal conglomerate. This is in sec. 9, T. 42 N., R. 31 W., along the Michigamme River. Here there is a thick mass of conglomerate overlain by southward-dipping schists. The conglomerate contains pebbles of extremely altered basic amygdaloidal rocks and of acid rocks which rest in a matrix of chlorite-schist. This detrital rock is such as might be derived from the Hemlock volcanics, but between it and these volcanics is found a mass of ferruginous muscovitic and chloritic schists at the Glidden exploration (sec. 32, T. 43 N., R. 31 W.), which are very similar to those occurring immediately south of the conglomerate, and like them have apparently a southern dip. The true relations between this conglomerate and the schists at the Glidden workings are not certain. The conglomerate may be below them. In that case the Glidden schists would correspond to those south of the conglomerate, the beds having received their present distribution from the close folding to which they have been subjected.

If such be the case, the schists at the Glidden are the northern limb of a syncline, and the conglomerate and the overlying schists, with an average dip of 70° S., represent the southern limb of a steep anticline, whose crest and northern limb have been cut off and covered up. The considerable width of the conglomerate exposed may be partly due to the fact that it has been doubled upon itself.

That the folding in this part of the district was probably fully sufficient to produce such structural relations and also the petrographical changes of the conglomerate matrix to a chloritic schistose mass is shown by the changes which the sedimentaries south of them in this part of the district have undergone. If this interpretation is correct, the space between the schists at the Glidden exploration and the Hemlock volcanics should be occupied by the equivalents of the conglomerate. Section K–L, Pl. VI, embodies this idea of the structure.

RELATIONS TO INTRUSIVES.

The Upper Huronian, as well as the Lower Huronian, has been penetrated by intrusive rocks. The difference in the character of the intrusives of the two series is, however, interesting. As has been seen (p. 77), the Lower Huronian is cut by vast masses of basic rocks and by rare dikes of acid rocks. In the Upper Huronian of the southern part of the district the acid rocks are more abundant but still subordinate to the basic intrusives. North of Crystal Falls is a great east and west basic dike. Similar rocks are known in a few small bosses near Crystal Falls. Moreover, on the Michigamme River, in secs. 31 and 32, T. 43 N., R. 31 W., and in a few places to the southeast of this area, the Upper Huronian is cut by the southern continuation of the basic masses whose principal occurrence is in the Lower Huronian area. Finally basic and ultrabasic intrusives pierce the Upper Huronian sediments in secs. 15, 28, and 29, T. 42 N., R. 31 W., and in a few other places. The acid rocks occur in isolated knobs near Crystal Falls, in sec. 28, T. 43 N., R. 32 W., and in sec. 4, T. 42 N., R. 32 W. They increase in quantity toward the southeast, and in the vicinity of Lake Tobin, in secs. 21 and 28, 42 T. N., R. 32 W., they form a series of small hills rising boldly out of the sand plains; and finally they occur in large quantity in secs. 19, 20, and 29, T. 42 N., R. 31 W., between the Paint and the Michigamme rivers.

CORRELATION.

The Upper Huronian sedimentary rocks were first studied in the field by Brooks, and the conclusion reached by him that they are late Huronian.[1]

Rominger correlates these same rocks very correctly with the schists exposed around Lake Michigamme, although he has the erroneous idea that they follow down the Michigamme River, instead of making a wide curve to the west, as subsequent study of the area has shown.[2] He considers the rocks as forming the middle portion of his Arenaceous Slate group.[3]

Recent work in the district has shown the Upper Huronian rocks to be

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[1] Geology of the Menominee region, by T. B. Brooks: Geol. of Wisconsin, Vol. III, 1880, p. 44.

[2] "The mica-schists seem to continue southward along the course of the Michigamme River, as we find in its lower course, 5 or 6 miles north from its entrance into the Brulé River, and from there down to the mouth, mica-schist to be the prevailing surface rock. Along the lower course of the adjoining Paint River the mica-schists likewise are the only rocks seen in the exposures." (Geol. of Michigan, Vol. V, 1895, p. 81.)

[3] Op. cit., p. 79.

unquestionably the western continuation of the Michigamme formation, to which the rocks correspond petrographically. The Michigamme formation has recently been carefully studied by Van Hise, and described by him in detail in Monograph XXVIII (Chap. IV). A less detailed description is given in the Fifteenth Annual Report (pp. 598–604). Since such great petrographical similarity between the Upper Huronian deposits in the western half of the Crystal Falls district and the above formation in the adjoining districts exists, and since nothing of exceptional interest has been observed in their study, the reader is referred to the articles mentioned for details. The following general description, while based upon the study of many exposures, specimens, and 75 sections of these Crystal Falls rocks, may still be considered to some extent as an abstract of the above articles in which the few changes made necessary by the slightly different characters have been incorporated.

PETROGRAPHICAL CHARACTERS.

From the above general statement it is seen that the Upper Huronian comprises rocks both of sedimentary and of igneous origin.

The preponderant deposits of the western half of the Crystal Falls district were muds and grits. With these were subordinate quantities of carbonates. In a few places sheets of basic rocks were intruded between the sedimentary beds and are now found alternating with them. Widely distributed basal conglomerates, coarse quartzitic conglomerates, and quartzites, such as characterize the lowest horizon (the Goodrich quartzite) of the Upper Huronian of the Marquette district, are absent. Work already completed outside of the immediate area covered by this report shows the presence of a small area of surface volcanics associated with the modified Upper Huronian sediments. This evidence of contemporaneous volcanic activity is closely paralleled by the Clarksburg volcanics of the Upper Marquette of the adjoining district.[1]

SEDIMENTARY ROCKS.

The sedimentary rocks of the Upper Huronian series in the western part of the Crystal Falls district are graywackes, ferruginous graywackes; micaceous, carbonaceous, and ferruginous clay slates and their crystalline

[1] Fifteenth Ann. Rept. U. S. Geol. Survey, cit., pp. 604–607; Monograph U. S. Geol. Survey, Vol. XXVIII, cit., pp. 460–486.

derivatives; and thinly laminated cherty siderite-slate, ferruginous chert, and iron ores. With these we find only in two places rocks of a well-developed conglomeratic nature.

Some of the rocks have undergone great metamorphism, and we find the graywackes and slates passing into chlorite-schists, mica-schists, and mica-gneisses. The ore deposits of the district are associated with the least altered sedimentaries.

The graywackes and slates are found chiefly in the northern and western parts of the district, while the single conglomerate, the metamorphosed or micaceous graywackes and slates, the mica-schists, and the mica-gneisses are confined to the southern portion.

Near Crystal Falls on both banks of the river, between the wagon and railroad bridges, there is exposed a conglomeratic phase of graywacke. Several bands of these coarse conglomeratic graywackes are interlaminated with bands of fine-grained graywacke and chert. A well-developed chert reibungsbreccia is also associated with these. I do not consider this conglomeratic graywacke as representing anything more than a purely local and very slight unconformity. This is evidently the same occurrence of conglomerate which has already been mentioned by Wadsworth.[1]

The well-developed conglomerate found in sec. 9, T. 42 N., R. 31 W., along the Michigamme River, contains pebbles of both basic and acid eruptive rocks in a chlorite-schist matrix. Toward the south the rock grades up into chloritic graywackes and chlorite-schists, which possess the ordinary characters of similar rocks in other portions of the area. The graywackes and slates of the district in general differ from each other chiefly in coarseness of grain. They are commonly interbedded in the same exposures. The rocks vary in coarseness from medium-grained graywacke to aphanitic slates, and in color from gray to green and black, the aphanitic slates being usually the darkest. These fine-grained rocks always show well-developed slaty cleavage. Throughout the area the rocks are very thoroughly consolidated, and in places where they have been most altered they are completely crystalline schists.

The crystalline rocks which are believed to have developed from the clastics are found in the southern portion of the district, beginning in sec. 16, T. 42 N., R. 31 W., and are well exposed in the river section at Nor-

[1] Sketch of the geology of the iron, gold, and copper districts of Michigan, by M. E. Wadsworth: Ann. Rept. State Board of Geol. Survey for 1891–92, 1893, p. 128.

way carry (portage). The rocks at this point are an alternating succession of mica-schists, some of which are very quartzitic, and hornblende-gneisses (altered igneous rocks) in thick beds. In these the bedding and schistosity agree, or else differ so slightly as not to be noticeable. These rocks outcrop in bold knobs for some distance away from and on both sides of the Michigamme River at the carry and also form the steep cliffs between which the river flows. In some places they are more or less ferruginous, and at one point near the head of the rapids exploring for iron has been done.

These crystalline schists are separated from the undoubted sedimentaries at the north by an interval of about one-half mile, and are separated to the south by a smaller interval from the next rocks, which are also of sedimentary origin, though of highly metamorphosed character. These latter consist of micaceous graywackes which grade over by increasing metamorphism into rocks which are indistinguishable from mica-schists and mica-gneisses. There can be no doubt as to the clastic character of these rocks, as one may see on the outcrops of the least altered phases the normal as well as the false bedding. The bedding of these micaceous graywackes agrees with that of the mica-schists at the Norway carry, and in them the schistosity is usually nearly parallel to the bedding, though at times cutting it at varying angles. These rocks vary in grain from fine to very coarse. They are most all a light-gray color. In two cases the presence of large porphyritic crystals of staurolite was observed. Garnet was found in but a single specimen, and no andalusite was seen. The scarcity or absence of such minerals is made noticeable by the fact that they are so abundant in the adjoining Marquette district. The contrast is the more marked since the Crystal Falls rocks are cut by and included in granite, and in the Marquette district these intrusives are absent. Splendid sections through the metamorphosed sediments are offered by the river sections in secs. 14, 24, 35, and 36, T. 42 N., R. 32 W., on Paint River, and at Peevie[1] Falls, sec. 32, T. 42 N., R. 31 W., on the Michigamme River.

It should be noted that thus far no grünerite-schists which owe their origin to the metamorphism of ferruginous sediments have been observed in the Crystal Falls district; nor does the brilliant red jasper—jaspilite—which accompanies certain of the ores in the Marquette district, occur associated in large quantity with them in the Crystal Falls district.

[1] This name has been given by the lumbermen to the falls as they lose so many peevies here in breaking jams.

The iron-bearing rocks of the Upper Huronian comprise cherts, siderite-slates, ferruginous cherts, iron ores, and subordinate quantities of ferruginous graywackes and clay slates.

The least altered of these is a siderite-slate. This is a fine-grained gray rock composed almost entirely of siderite, usually in rounded rhombohedral crystals, with very little minutely crystallized silica between them in places. Wherever they have been exposed to the weather any length of time, these rocks have a deep reddish-brown oxidation crust. Alteration also follows along crevices, and thus the siderite is rapidly oxidized. The main products derived from these siderites are like those of the more important ore-producing parts of the Penokee and Marquette districts, namely, hematite and limonite. Little magnetite has been found. These siderites are interbanded with the black carbonaceous clay slates. In some cases the dividing line is sharp. In others, as the siderite lessens in quantity, fragmental material increases until only a few crystals of siderite are found scattered through the clastics. Their association with the carbonaceous fragmentals would seem to indicate, as pointed out by Van Hise,[1] that the siderite owes its formation to the presence of organic material.

The ferruginous cherts (the term is here used as defined by Van Hise) are banded chert and hematite, with some magnetite, in which the iron oxide is derived from a previously existing siderite, and the cherty bands are not of fragmental origin. This alteration from the siderite to hematite may be easily followed from the fresh siderite through that which is slightly discolored, to the reddish-brown earthy mass, and then to the crystalline hematite. Such alteration processes have been illustrated and clearly described a number of times by Van Hise, so that no further mention will be made of them.

The ferruginous graywackes may be described as rocks which are partly of fragmental and partly of chemical origin. For instance, the transition may be traced from a rather micaceous magnetitic graywacke, in which ordinary and false bedding may be seen, to a rather schistose rock, in which magnetite is predominant, but in which is considerable fragmental quartz and secondary muscovite and chlorite. This rock represents an original grit containing more or less siderite. Metamorphism has changed

[1] Fifteenth Ann. Rept. U. S. Geol. Survey, cit., p. 601; Mon. U. S. Geol. Survey, Vol. XXVIII, cit., p. 447.

the siderite to magnetite, and produced from the fine fragmental mud the muscovite and chlorite.

MICROSCOPICAL DESCRIPTION OF CERTAIN OF THE SEDIMENTARIES.

In the following pages I shall describe in a brief way the graywackes and slates, the most common rocks of the district, and the rocks which have been produced from them by metamorphism.

The graywackes and slates consist chiefly of readily distinguishable fragmental quartz and feldspar grains, which are embedded in a matrix consisting of fine-grained quartz, feldspar (?), biotite, muscovite, chlorite, some siderite, epidote, small quantities of magnetite, hematite, and iron pyrites, and a dark clayey mass. This mass appears to contain a considerable amount of black carbonaceous material and reddish-brown ferruginous matter in finely disseminated specks. The greater the quantity and finer the character of this matrix the more difficult it becomes to determine its constituents with any degree of certainty. In the slates the matrix plays the chief rôle, while in the graywackes the large fragmental grains form the predominant material. By a diminution in quantity of the matrix and fragmental feldspar grains, the coarser-grained clastics approach very closely to true quartzites, but in no case was a pure quartzite found.

The constituents which can be recognized without difficulty as original ones are the larger grains of feldspar and quartz. These show pressure phenomena of all grades, from slight, wavy extinction to complete granulation. Many of the large fragmental quartzes are mashed into oval-shaped areas or are broken into numbers of fragments. The large feldspars are broken, and are altering to quartz and secondary clear feldspar with a simultaneous production of epidote and mica. In their least altered condition the original feldspars are cloudy, and hence may be readily distinguished from the limpid secondary grains.

The small mineral particles of the matrix, including the mica, do not show undulatory extinction like the large fragmental quartzes and feldspars. These micaceous minerals are in automorphic plates, and wrap around the quartz grains, and in some cases likewise project into them. These constituents of the matrix are all believed to be secondary minerals derived from the original clayey matrix, and from the alteration of the feldspar fragments, with the possible addition of infiltrated material. At places all

of these minerals occur together, but more commonly one finds various combinations of certain of them. When muscovite is present in large quantity, it is usually not accompanied by biotite or chlorite, the iron and magnesium necessary for the production of biotite and chlorite evidently not having been present. These last two, however, are always associated. As the mica increases, the schistosity of the rock increases in a corresponding manner, and the rocks become those which may be spoken of as micaceous graywackes.

These micaceous graywackes represent a somewhat more advanced stage of metamorphism of the rocks than the graywackes just described, and the extremely altered varieties of these are very close to the mica-schists and mica-gneisses, according to the respective amounts of secondary feldspar present. No distinction, however, can be made in the field between some of the less metamorphosed graywackes and these micaceous ones. The chief difference appears to be in the fact that in the micaceous graywackes the larger feldspars are almost completely altered and the finer matrix completely recrystallized into readily distinguishable mineral particles. In these more metamorphosed rocks the parallel intergrowth of secondary muscovite and biotite is nicely shown, a thin leaf of biotite being included between two lamellæ of muscovite. A considerable quantity of epidote is scattered in large grains through the micaceous graywackes, besides occurring in aggregates of small grains. Some crystals of apatite and tourmaline were observed. Rutile is found in some quantity, and with it is also sphene, both of them possibly resulting from the alteration of titanium-bearing iron ores in the original graywackes. The iron present in the original graywackes as siderite and the minute specks of oxide have been collected into large crystals of magnetite and also into aggregates of smaller, well-defined magnetite crystals.

The alteration of the feldspar and the production from it of quartz, secondary feldspar, epidote, and mica is well shown in one case. In this the nucleus of original feldspar, in the center, contains minute grains of epidote and flakes of muscovite, besides reddish, presumably ferruginous, specks. These with a low power cause the feldspar to appear cloudy. Surrounding this core is a mottled zone in which secondary feldspar and quartz occur. In one place in this zone a flake of biotite is observed. Some epidote also occurs in it, but no muscovite.

The alteration of the feldspar usually begins at the periphery, and gradually advances toward the center. It thus breaks the original grain up into irregular areas and stringers of feldspar, many of which are attached to the unaltered center. Between these residual areas of feldspar there are irregular grains of secondary limpid feldspar and quartz. The farther the alteration is advanced the less of the irregular center may be seen, and in the final stage the feldspar core disappears.

While the alteration nearly always begins at the periphery, one case was noticed where it apparently began at various places in the grain, the result being the production of a secondary micropoikilitic structure. This original feldspar is cloudy, with the usual alteration products, but scattered through this are a number of more or less roundish spots of quartz, the majority of which extinguish simultaneously, and have a different position of extinction from the including feldspar. Considering these two elements alone, the structure is near the micropegmatitic; but there are other areas which extinguish in different positions from both the quartz and the original feldspar. These are of decidedly more angular shape than the secondary quartzes, and appear to be secondary acid feldspar. The small size of these secondary minerals prevents the use of any physical tests other than the differences in refraction. The rounded quartz appears in many respects very much like the corrosion quartz of the French petrographers. The majority of the secondary feldspars are unstriated, but a few show striations. No satisfactory sections upon which to make measurements were found. Biotite and muscovite flakes are included in the quartz, and smaller automorphic plates of biotite may be seen lying partly within the altered feldspar grain, as though growing partly at its expense.

These highly metamorphosed micaceous rocks included under the general term "micaceous graywackes" have the interlocking groundmass structure of the schists, but some of the larger grains show clastic forms. No sharp line can be drawn between these metamorphosed sediments on the one hand and the mica-schists and mica-gneisses on the other.

In the mica-schists and mica-gneisses all of the original mineral grains have been completely crushed and recrystallized, and we can find no microscopical criteria which enable us to class them with the sedimentary rocks. Dynamic action in the district had sufficient power and duration to complete locally the metamorphism of the original sedimentaries and produce per-

fectly crystalline schists, as described by Van Hise in the Penokee and Marquette districts.[1] No rocks corresponding in content of carbon to the carbonaceous slates which occur among the rocks around Crystal Falls and south of that town have been found among these crystalline schists. These crystalline schists are throughout moderately fine grained, and consist of quartz, feldspar, and mica, with associated epidote, rutile, tourmaline, and iron oxides, and in a few exceptional cases crystals of staurolite and garnet. In some of the rocks quartz and mica are preponderant and feldspar is practically wanting, and we have mica-schists. In others all three essential minerals are present, and we have mica-gneisses. The presence of the feldspar, and to some extent the proportion of the mica and other minerals, depend on the character of the original sediments. Conclusive evidence of the sedimentary origin of these schists is furnished by their occurrence in the field, where are found all gradations between them and rocks of unquestionably sedimentary character.

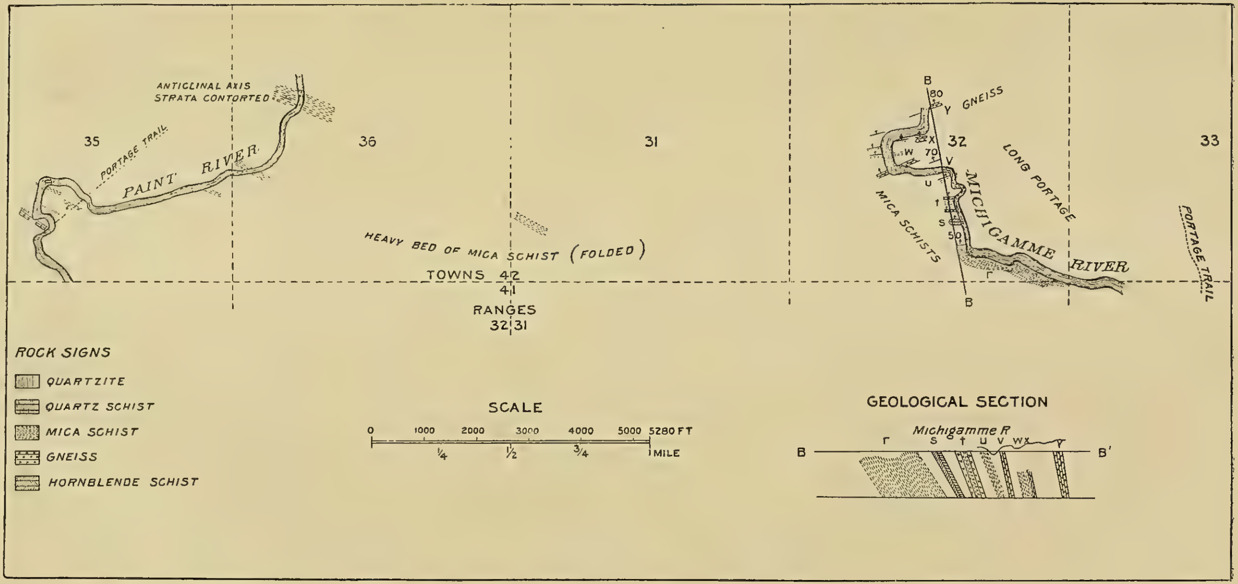
In Pl. XV there is reproduced the part of Brooks's Pl. IX in Vol. III of the Geological Survey of Wisconsin which comes within the Crystal Falls district and includes a part of the area underlain by the Huronian sediments. There is here given his macroscopical description[2] of the rocks collected in his study of the area.

Brooks's macroscopical description of rocks collected in the Crystal Falls district.

No. of bed.		Thickness in feet.
r.	*Mica-schist*, alternating with *gneiss*, generally flaggy or schistose (2452)	1,250
	About 1¾ miles west and a little north is an outcrop of *mica-schist* containing staurolite (2160). The same rock crosses the Paint 1 mile farther west and north, where it also contains staurolite. This is important and interesting, since this mineral characterizes the same bed of mica-schist (XIX) in the Marquette region, where it is associated with andalusite. Neither mineral has been observed elsewhere in the series.	

[1] Mon. U. S. Geol. Survey, Vol. XIX, cit., pp. 332-343; Mon. U. S. Geol. Survey, Vol. XXVIII, cit., pp. 449-450.

[2] Geology of the Menominee iron region, by T. B. Brooks: Geol. of Wis., Vol. III, 1880, Pt. VII, p. 496.



PORTION OF BROOKS'S PL. IX, VOL. III, WISCONSIN GEOLOGICAL SURVEY, SHOWING DETAILS ON PAINT AND MICHIGAMME RIVERS.

Brooks's macroscopical description of rocks, etc.—Continued.

No. of bed.		Thickness in feet.
s.	*Hornblende-schist* or *gneiss*, black, slaty, banded with gneissic layers (2453)	100
t.	*Gneiss* and *mica-schist*	300
	Covered	150
u.	*Staurolitic mica-schist* on south, overlaid with *mica-schist* and *gneiss* (2455)	400
	Covered	150
v.	*Gneiss*	100
w.	*Mica-schist*	100
x.	*Micaceous quartz-schist* or *gneiss* (2381, 2457)	250
	Covered	500
y.	*Gneiss*	150

He then mentions the occurrence farther up the Michigamme River of exposures of "a heavy bed of *gneiss*, dipping north at a high angle," and also speaks of "outcrops along the river of *hornblendic* and other rocks, often *granitic* in appearance." He writes also of "chloritic and hornblende schists exposed for a thickness of over 1,000 feet" at the Norway portage, farther up the river. "They dip south at a high angle under the granite hornblende belt just described, and are probably the equivalents of some portion of the Long Portage series on the opposite side of this synclinal, although these differ from the prevailing rocks of that series in being decidedly more chloritic and hornblendic.[1]

It is seen from the above quotations that the general characters of the rocks were recognized by Brooks. His schists are for the most part the metamorphosed sediments, and the hornblendic and granitic rocks are the various basic and acid rocks which intrude them.

Specimens from these interesting beds were collected by the Michigan and Wisconsin surveys, and were described by Julien, Wichmann, and Wright in lithological reports appended to the reports of those surveys.[2]

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[1] Geology of Menominee iron region, by T. B. Brooks: Geol. of Wis., Vol. III, 1880, Pt. VII, p. 497.

[2] Microscopical observations on the iron-bearing rocks from the region south of Lake Superior, by Arthur Wichmann: Chapter V of Brooks's Geology ofthe Menominee iron region, Geol. Survey of Wis., Vol. III, 1880, pp. 600–656.

Lithology, by A. A. Julien: Geol. of Mich., Vol. II, 1873, pp. 1–197. Appendix A.

Geology of the Menominee iron region, by C. E. Wright: Geol. Survey of Wis., 1880, part 8, pp. 690–717.

Specimens of these mica-schists and chlorite-schists were regarded by Wichmann as nonfragmental.[1] This is little to be wondered at, since he had never studied their field relations. In the field these rocks can, however, be traced into rocks of unquestionably fragmental origin. The same specimens were described as "micaceous quartz-schists" by Wright.[2] Wright also mentions a staurolitiferous mica-schist in the Michigamme River, and also in the Paint River. The second occurrence is 2½ miles northwest from the first and in the direction of its strike. Julien describes metamorphic rocks from Long Portage as "fine-grained grayish black gneisses."[3] From these descriptions it is seen that the least altered sedimentaries on the one hand and the crystalline schists on the other were recognized by these earliest students of the metamorphic rocks. However, the fact to which I would especially call attention, that the crystalline schists are derived from the clastic rocks by metamorphism, was evidently not understood.

The contact action produced by igneous intrusions into these series of sedimentaries will be discussed in connection with the intrusive rocks (p. 194 et seq.).

IGNEOUS ROCKS.

The igneous rocks which are found to have penetrated the Upper Huronian after the important folding of the rocks took place are not included here, but may be found described under the heading "Intrusives" (p. 187). In this place it is desired to call attention to certain hornblende-gneisses which occur near Norway carry, on the Michigamme River, and also extend in large outcrops west of the river for about 2 miles and east for about a mile. These are interlaminated in thick masses with the mica-schists. They are perfectly crystalline hornblende-gneisses. They consist of common hornblende, quartz, feldspar, and some iron oxide. The hornblende is present in large quantity, the parallel plates of that mineral giving the rock its schistosity. None of the minerals are automorphic, but all occur in interlocking grains. Without going into a detail description of these rocks, it will suffice perhaps to state that they are similar in all respects to hornblende-gneisses which in other parts of the Lake Superior

[1] Op. cit., pp. 635, 646.

[2] Op. cit., p. 693.

[3] Op. cit., p. 130.

[4] Bull. U. S. Geol. Survey No. 62, by G. H. Williams, 1890; Mon. U. S. Geol. Survey, Vol. XXVIII, pp. 152–159, 203, 208.

region have been traced into igneous rocks.[4] These gneisses are believed to be igneous rocks, either intrusives which were injected parallel to the bedding of the Upper Huronian sediments prior to the folding, or contemporaneous volcanics. They have been metamorphosed and rendered schistose by the same forces which metamorphosed the sediments. This explains the perfect agreement of their schistosity with that of the adjacent sediments.

ORE DEPOSITS.

HISTORY OF OPENING OF THE DISTRICT.

For a number of years after the opening of the mines of the Menominee range, prospectors worked in various places, among others in the vicinity of Crystal Falls, seeking to follow the iron range west of the Menominee River. As a result of this endeavor, the deposits at Florence, Wisconsin, and then those farther north and west at Crystal Falls, Michigan, were in turn located. It was not until 1881 that sufficient exploratory work had been done at Crystal Falls to warrant a belief in the future of this iron-bearing area. In April, 1882, the Chicago and Northwestern Railway completed its branch to Crystal Falls, and the shipment of ore began. The Amasa deposits were not exploited to any great extent until the year 1888, when the Chicago and Northwestern Railway built a branch from Crystal Falls to Amasa. The Chicago, Milwaukee and St. Paul Railway, in 1893, completed a line from Channing to Sidnaw, which runs through Amasa.

DISTRIBUTION.

The iron-bearing rocks trend northwest and southeast from Crystal Falls. East of Crystal Falls some of the ore deposits are found in proximity to the Hemlock volcanics, and follow along a line located a short distance from them. Other deposits are those at Amasa, about 12 miles northwest of Crystal Falls. These are near the contact between the Upper Huronian and Lower Huronian, and above the Hemlock volcanics, like the deposits east of Crystal Falls. Four miles north of Amasa are the explorations in sec. 20, T. 45 N., R. 33 W., in which the iron-bearing beds are exposed. Another exposure of the iron-bearing formation is in sec. 34, T. 46 N., R. 33 W., about 4 miles still farther north.

These are the northernmost known exposures of the iron-bearing rocks of the Upper Huronian in the Crystal Falls district. However, dial-compass and dip-needle work has located a line of magnetic attraction for

about 12 miles to the north and east. By means of this line of magnetic attraction, with the assistance afforded by occasional outcrops of Lower Huronian, Hemlock volcanics, the possible continuation of the iron-bearing belt was approximately located.

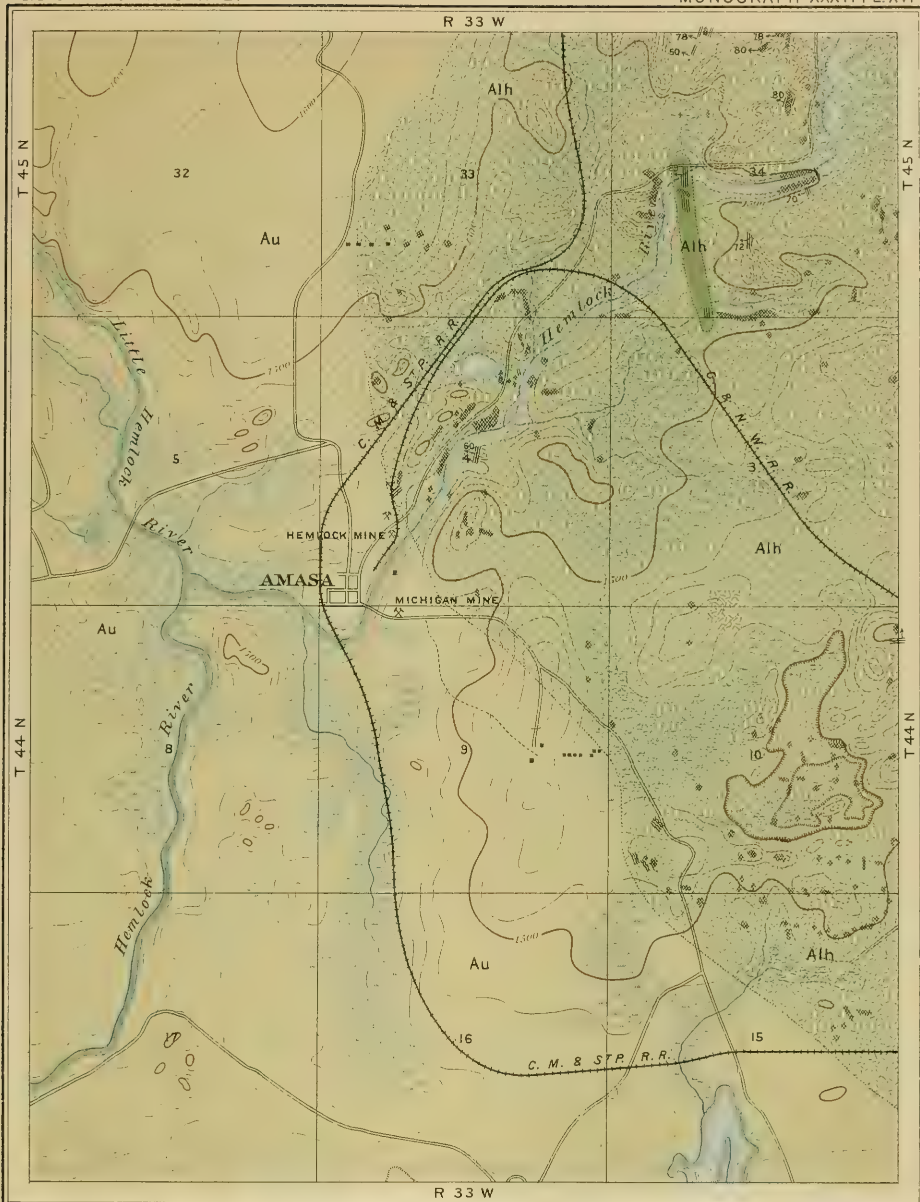
I shall take up the four localities mentioned in which an iron-bearing formation has been found, and discuss them in some detail, beginning at the northern and least important and passing to the southern and most important part of the district.

WESTERN HALF OF SEC. 34, T. 46 N., R. 33 W.

In the western half of sec. 34, T. 46 N., R. 33 W., there are outcrops of a magnetic graywacke which grades into a rock that might properly be called a magnetite-schist but for the fact that its partial fragmental nature is still apparent. The rock contains a varying quantity of magnetite, always enough to exercise great influence over the magnetic needle. However, in no case have true ore deposits been found in it, although the vicinity has been extensively test pitted. The strike is in general north and south, with a high dip to the west, thus agreeing in general character with the trend of the Hemlock volcanics. The highest outcrop of the volcanics is a schistose amygdaloid. After an interval of no exposure of about 30 feet, graywacke appears, and this grades up into the magnetitic beds.

SEC. 20, T. 45 N., R. 33 W.

To the south, in sec. 20, T. 45 N., R. 33 W., are outcrops of ferruginous chert, which in places contains "bands and shots" of ore, the thicker bands being an inch and a half across. These outcrops have tempted prospectors to do considerable exploring by means of both test pits and diamond-drill holes. The results have been negative. The general map, Pl. III, shows that the Upper Huronian at this place indents the Lower Huronian series, indicating, as has already been said, the presence of a westward-pitching syncline. The presence of this syncline is further shown by the strike obtained on the outcrops of chert found at this locality. For the most part, a nearly north-south strike prevails. The greater part of the northern ledges give an east-west strike, with a variation of but a few degrees to the north of east. The southernmost outcrops show a strike which varies from N. 27° E. to N. 34° W. The dip is in all cases high, ranging from 80° to



JULIUS BIEN & CO. LITH. N.Y.

DETAIL GEOLOGICAL MAP
OF
VICINITY OF AMASA, MICHIGAN

SCALE: 2 INCHES = 1 MILE   CONTOUR INTERVAL 20 FEET

Outcrops without observed strike or dip
Outcrops with determined strike and dip
Outcrops with slatiness or schistosity
Test pits bottomed in rock

ALGONKIAN

LOWER HURONIAN — HEMLOCK FORMATION: Volcanics (Alh); Normal Sediments (Alh)

UPPER HURONIAN — UNDIVIDED (Au)

87°. The severe deformation is clearly shown by the plication of the beds, and by faults whose extent can not be determined, but which are accompanied by rather extensive reibungsbreccias. The breccias are cemented by iron oxide.

THE AMASA AREA.

The Amasa deposits must of necessity be very briefly described, as I have been unable to obtain much information concerning the relations of the rocks as shown in the closed mine. In the early days of the mine it was thought by the mine captain that the volcanics formed the foot wall of the ore, and on his authority Van Hise says, "The ore of the Hemlock mine rests upon a stratum consisting of surface volcanic material."[1]

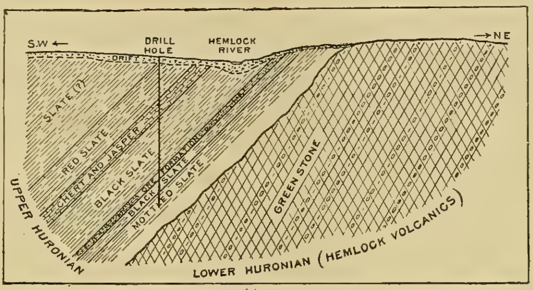


FIG. 11.—Profile section illustrating results of diamond-drill work.

Probably this is a mistake, for the section from west to east (fig. 11), i. e., from the higher to the lower beds, obtained in two drill holes, is as follows:

	Feet.
Gray sericitic slate, discolored by iron	115
Chert and jasper	59
Pyritiferous black slate and quartzite	180
Ore formation	30½
Magnetitic slate	42
Mottled slates, red and green, containing iron. Drilling ceased after passing through	70

The thickness of the beds given is the true one and not the thickness passed through by the drill, which cut through the beds at an angle. These beds projected to the surface are found to be immediately underlain by greenstone, in some places massive, in others tufaceous. Moreover, an identical section is shown by a drill hole 4 miles southeast of Amasa, in sec. 26, T. 44 N., R. 33 W. It was carried deeper, however, and after passing through the mottled slate was bottomed in greenstone. From these drill

[1] The iron ores of the Marquette district of Michigan, by C. R. Van Hise: Am. Jour. Sci., vol. 43, 1892, p. 130.

holes it appears certain that the ore formation is immediately underlain and overlain by black slates. The foot and hanging slates are much alike, the hanging, however, being very pyritiferous, and the foot containing much more iron than the hanging. This iron is in the form of hematite and magnetite. Below the black magnetic slate is the ferruginous mottled slate, which apparently lies next to the Lower Huronian Hemlock volcanics. The so-called ore formation consists of banded chert and jasper, with which the hematite bodies are associated.

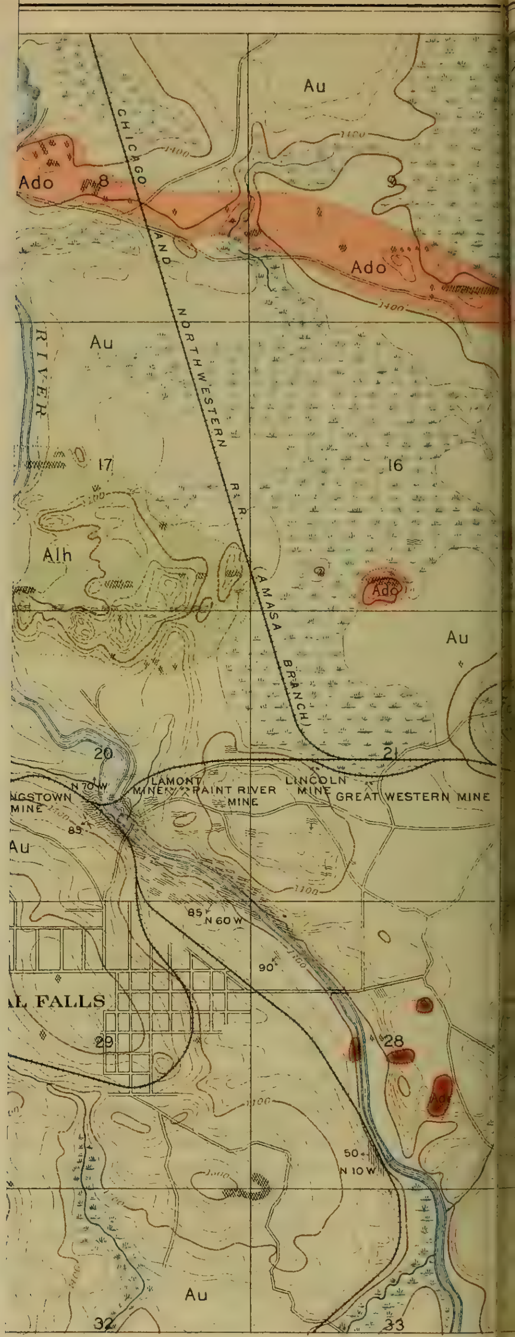
The results obtained from these holes show the lenticular character of tne ore bodies and the difficulty in finding them. One of the holes passed through the ore formation, but missed the ore body, which subsequent underground work showed it would have struck had it cut the formation 50 feet farther north.

The distribution of the Huronian rocks in the vicinity of Amasa is shown on the map, Pl. XVI.

THE CRYSTAL FALLS AREA.

The most of the observations upon the ore bodies and their relations to surrounding beds have naturally been made in the vicinity of the town of Crystal Falls, where, owing to the extensive development of the mines, the underground conditions could best be studied. The conclusions reached, however, are confidently believed to hold good for the entire Upper Huronian of the district.

In the description of the folding of the Upper Huronian it was stated that the Crystal Falls area is in a synclinorium forking as the result of a subordinate central anticline so as to produce a U opening to the south of west. It is in this basin that the important mines of the Crystal Falls district are situated. One row of mines—the Hollister, Armenia, Lee Peck, and Hope—as shown by the map (Pl. XVII), lies to the west and northwest of the main mass of Hemlock volcanics between Crystal Falls and Mansfield. A second and more important set of mines follows an east-west line south of the subordinate area of volcanics, which lie just north of Crystal Falls in the midst of the Upper Huronian sediments. The second set of mines, including the Crystal Falls, Great Western, Lincoln, Paint River, Lamont, Youngstown, and Claire, lies near the axis of the syncline—that is, along the line of major folding, and consequently greatest mashing. The



GEOLOGICAL MAP OF THE VICINIT

SCALE, 2 INCHES – 1 MI

Outcrops without observed strike or dip

LOWER HURONIAN

MANSFIELD SLATE

Alm

HEMLOCK FORMATION

Alh

RYSTAL FALLS AND MANSFIELD.

CONTOUR INTERVAL, 20 FEET

rmined strike and dip

omed in rock

Outcrops with slatiness or schistosity

KIAN

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DOLERITE

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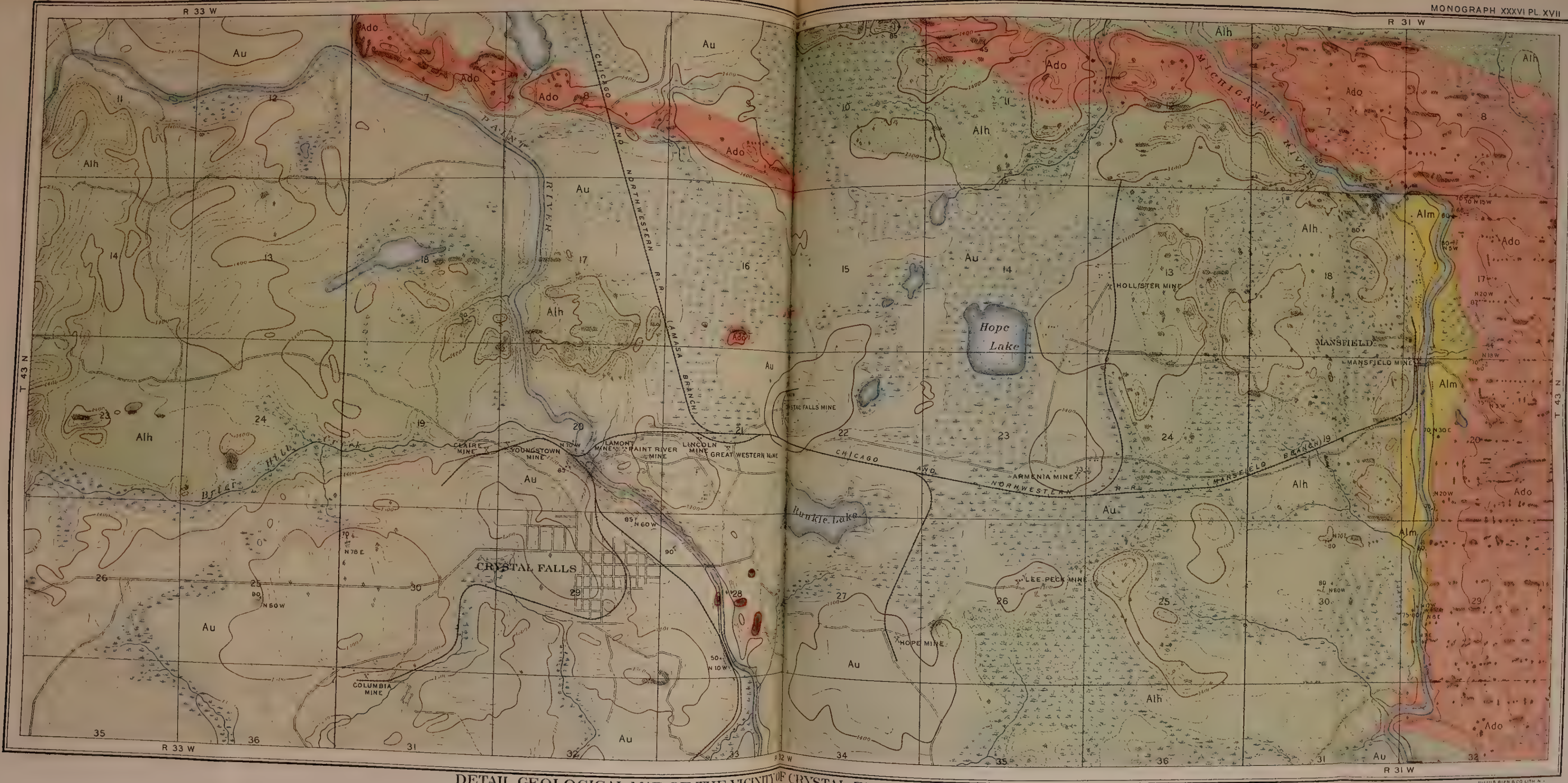

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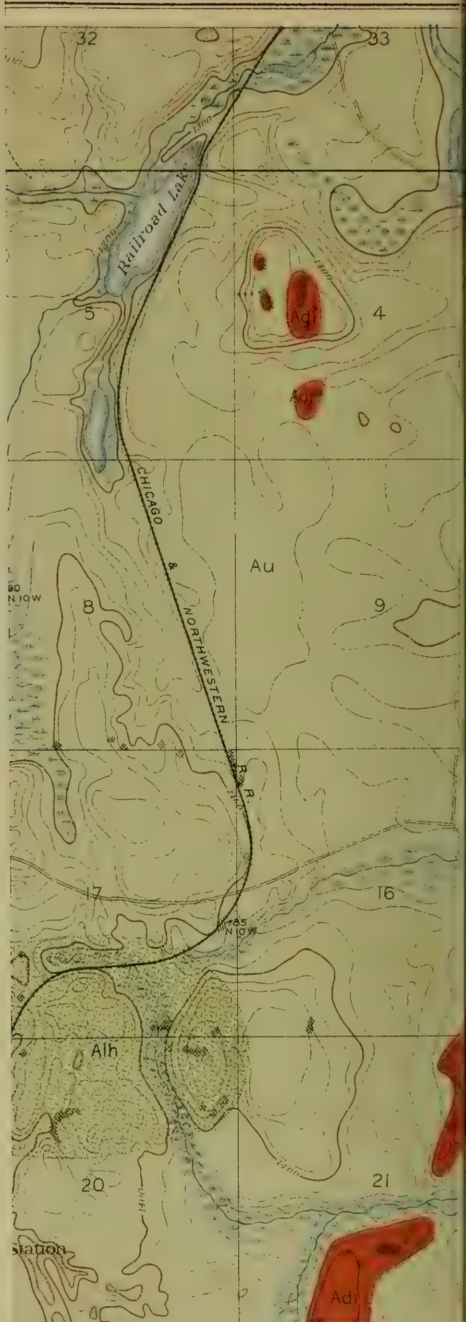
DETAIL GEOLOGICAL MAP OF THE VICINITY OF CRYSTAL FALLS AND MANSFIELD. SHEET I

SCALE, 2 INCHES = 1 MILE CONTOUR INTERVAL, 20 FEET

Outcrops without observed strike or dip
Outcrops with determined strike and dip
Outcrops with slatiness or schistosity

ALGONKIAN

LOWER HURONIAN		UPPER HURONIAN UNDIVIDED	INTRUSIVE	
MANSFIELD SLATE	HEMLOCK FORMATION		DOLERITE	DIORITE
Alm	Alh	Au	Ado	Adi



GEOLOGICAL MAP OF THE VICIN

SCALE, 2 INCHES - 1

Outcrops without observed strike or dip

Ou

LOWER HURONIAN	UPPER HURONIAN
HEMLOCK FORMATION	UNDIVIDED
Alh	Au

RYSTAL FALLS AND MANSFIELD

CONTOUR INTERVAL, 20 FEET

ined strike and dip

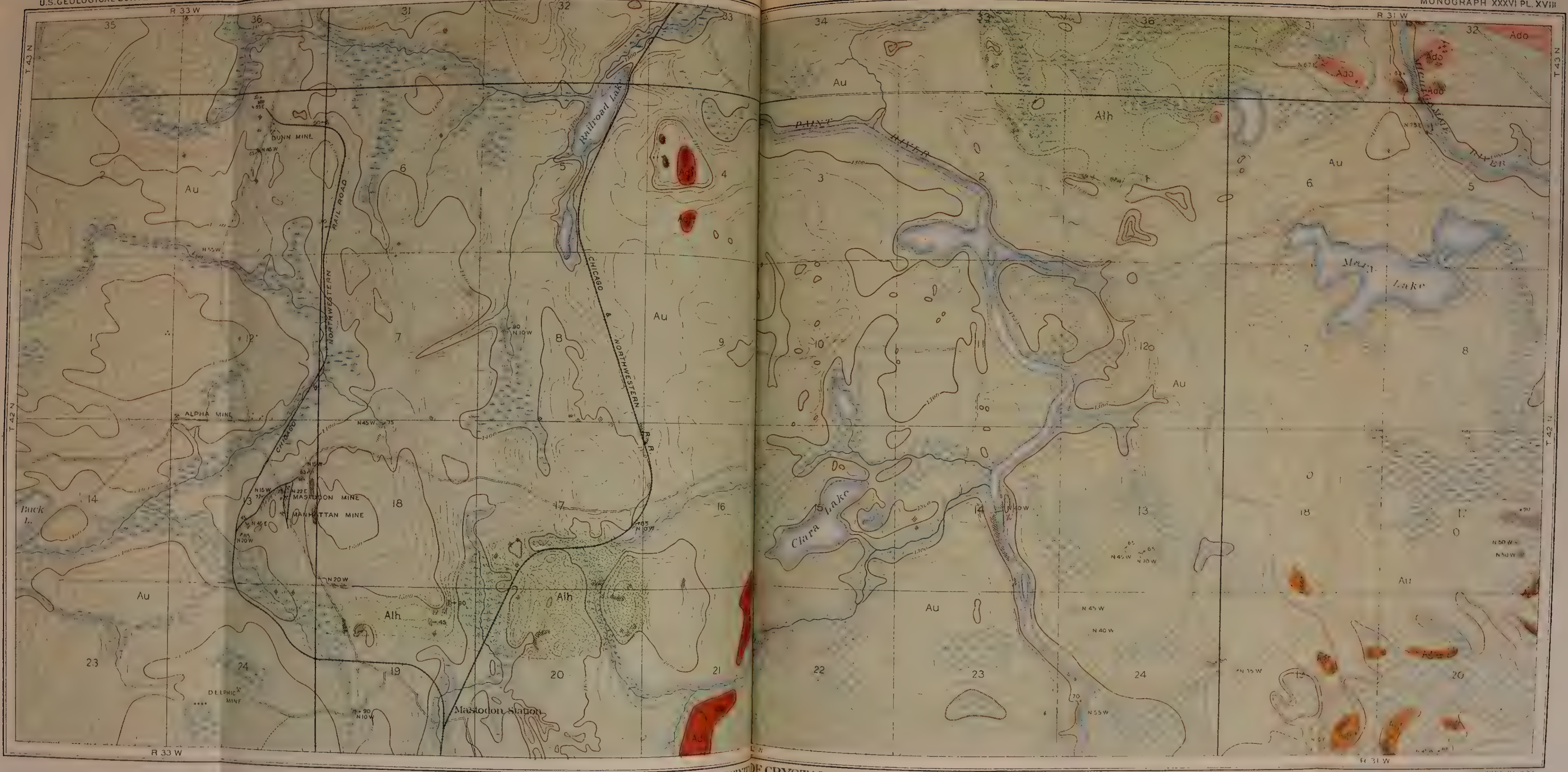
Outcrops with slatiness or schistosity

ned in rock

IAN

INTRUSIVE

TE	DIORITE	GRANITE
	Adi	Agr



DETAIL GEOLOGICAL MAP OF THE VICINITY OF CRYSTAL FALLS AND MANSFIELD. SHEET II

SCALE, 2 INCHES=1 M

CONTOUR INTERVAL, 20 FEET

Outcrops without observed strike or dip — determined strike and dip — Outcrops with slatiness or schistosity

ALGONKIAN

LOWER HURONIAN	UPPER HURONIAN		INTRUSIVE	
HEMLOCK FORMATION	UNDIVIDED	DOLERITE	DIORITE	GRANITE
Alh	Au	Ado	Adi	Agr

Columbia, Dunn, Mastodon, and others to the west (Pl. XVIII), are probably the western continuation of this line of mines, and follow the trend of the main synclinal axis of the district. The position of these mines with reference to the main structural features of the district can be seen on the relief map and the sketch map corresponding to it, Pl. XIV.

The section made through the closely folded Upper Huronian beds by

Fig. 12.—Sketch illustrating contortion of Upper Huronian strata.

the Paint River affords the best opportunity in the district for studying the rocks, but the rocks are so crumpled that even here the succession was not made out with certainty.

The sketch fig. 12, by W. N. Merriam,[1] shows the folding of the slate and chert strata as seen in the railroad cut between the Paint River and the Lincoln mine. The strike of the rocks is about N. 80° E. The sketch is taken looking almost along the strike of the beds. In fig. 13 a second sketch is given, also by W. N. Merriam, which illustrates the rapid change in strike in these beds, due to the contortion of the strata. This change is seen near the east end of the wagon bridge just across the Paint River from Crystal Falls. At this point the beds bend from a strike of S. 40° E. to W. 10° S. The change takes place by means of three very sharp bends.

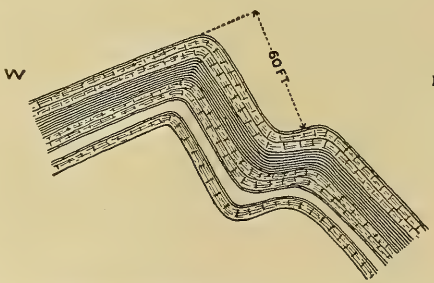


Fig. 13.—Sketch showing change of strike of Upper Huronian beds due to the folds.

The following are the observations made by Rominger upon these exposures near Crystal Falls:

Among the recently discovered productive fields for iron mining, the vicinity of Crystal Falls has become famous for its wealth in ore. The formation enclosing the ore

[1] Manuscript notes.

deposits, has there a great thickness, but its determination by actual measurement is impossible, on account of the much folded condition of the strata, and for want of connected exposures transverse to the stratification. Estimating its thickness to several thousand feet is surely not far beyond the truth. This folded condition of the strata is in many instances an obstacle in the decision, whether in a given locality we have under observation a descending or an ascending succession of beds.

If we follow the railroad from Crystal Falls village upward along the bed of Paint River, we find, in the first cut the road makes into rock beds, a series of hard, black slates, transversely intersected in almost vertical positions, and, according to their cleavage planes, dipping in southwest direction. This cross-cut is 210 steps long; thence, for the distance of 100 steps, no rock ledges are touched by the roadbed, but on the left side of the road similar slate rocks are denuded, which apparently represent a continuation of the former succession. From here for eighty steps a cut is made through similar slate rocks, but interlaminated with numerous quartzite seams; further on, the intersection of slates in alternation with quartz seams continues for quite a while, but these slate rocks are more graphitic than the former and readily disintegrate, on exposure, into splintery fragments, as they contain a large proportion of iron pyrites and rusty ferruginous seams causing the decay. By this time we have reached close to the river below its falls, and find, laid open in its embankments formed by the bluffs thirty feet high, a further conformable series of graphite-schists, 300 feet wide. Beneath the graphite-schists, close to the water level at the foot of the falls, succeeds an ore belt six feet wide at the surface, but widening to fifteen feet, followed into the hillside.[1] . . . . . .

Below the ore belt follows an immensely large succession of thinly laminated banded ferruginous quartz-schists of dark, rusty color, which beds, in steeply erected position crossing the river bed diagonally, give a cause to falls eight or ten feet in height. The exposed succession of beds amounts at the falls to a thickness of over 800 feet. Intermixture of pyritous shaly seams with the quartzite beds, induces their rapid disintegration on exposure, into shelly fragments covered with an iridescent varnish like coating of oxide-hydrate. These beds are, in the embankments on the opposite river side, remarkably corrugated, describing in their flections perfect coils.[2]

CHARACTER OF THE ORE.

The ore obtained from the Crystal Falls district is chiefly soft red hematite, though in places it is hydrated and graded as brown hematite (limonite). The ore is very porous and shows many crystal-lined cavities. At places a hard steel hematite ore is found, which runs as high as 70 per cent metallic iron. This ore occurs in very small quantities associated with the soft ores, and appears for the most part to have formed in geodal cavities. When the cavities are still partly open, the ore has botryoidal and stalactitic forms. The ores are very similar to the ores of the Michigamme

[1] Iron and copper regions of the Upper and Lower Peninsulas of Michigan, by C. Rominger: Geol. of Mich., Vol. V, 1895, Pt. 1, p. 74.

[2] Ibid., p. 75.

slates of the Upper Marquette series, but differ very considerably from those of the Lower Marquette series, in which the hard hematites and magnetites are important ores, and from the ores of the Menominee district, which produces large quantities of soft blue hematite, some martite, and also some specular ore.

The following figures show the average composition of the ores for the district. They were taken from analyses furnished by the management of the various mines and from the reports of the State commissioner of mineral statistics of Michigan.

The metallic iron of the ores ranges from 54 to 63 per cent, the average being about 59 per cent. Phosphorus in exceptional cases is as low as 0.05 per cent, though usually ranging from 0.1 to 0.7 per cent, most commonly approaching the higher figure. Silica averages about 3 per cent. These analyses show the ore to be rather low grade.[1] It is due to this that this district has been so sensitive to the prices of iron ores. A low market price makes the cost of production exceed the selling value, and under these conditions work necessarily stops.

Some of the ores in the Crystal Falls district contain a very high percentage of Al_2O_3, CaO, and also of manganese. It is reported that some very good deposits of manganese have been found, one unauthenticated statement being to the effect that an analysis of the ore runs as follows: Metallic iron, 17.46; manganese, 29.81; phosphorus, 0.064; silica, 0.009(?).

[1] Brooks states that "the ores are unlike those in the more easterly part of the Menominee region in being richer in iron, freer from silica, and in containing more water." (Analysis 68, p. 302.) Geology of Michigan, Vol. I, part 1, p. 182.

Since the above was written the volume on Mineral Resources of the United States, 1896, Part V, of the Eighteenth Annual Report of the United States Geological Survey, has appeared, and the following analyses of ores from the Crystal Falls district are taken from Mr. John Birkinbine's article on iron ores in that report.

The analyses were prepared for the ore association at Cleveland, Ohio, and show the average cargo analyses of iron ore as shipped from the various mines. The analyses were made from ores dried at 212°, the amount of natural moisture being added.

	Iron.	Silica.	Phosphorus.	Manganese.	Alumina.	Lime.	Magnesia.	Sulphur.	Organic and volatile matter.	Moisture.
Crystal Falls	58.55	4.25	.721	.20	1.16	2.64	.77	.008	2.92	7.20
Dunn	58.61	3.88	.573	.58	1.88	1.80	.83	.033	5.44	8.70
Hemlock	60.20	4.71	.309	.39	2.81	1.87	1.32	.010	....	6.62
Lincoln	60.86	3.86	.240	.45	1.67	2.14	1.73	.010	....	6.50
Mastodon	61.00	4.50	.350	.30	2.75	.50	.30	.075	....	9.00

One of the best results gives as high as 61.5 per cent metallic Mn. The ores thus range from a manganiferous iron ore to a manganese ore. The further statement is made that the bed lies very close to the surface, and is from 6 inches to 3 feet in thickness. From 4 to 6 feet of bog iron is found underlying the bed of manganese.

RELATIONS TO ADJACENT ROCKS.

The ore is associated with white or reddish chert, which in places is jaspery. The cherty iron formation passes into ore by a decrease of the silica. An intermediate phase is chert with "bands and shots" of ore. In places the chert is more or less brecciated, and the ore often has a similar character. Commonly the ore is completely surrounded by the chert beds, or chert and ore, forming the so-called mixed and lean ore. In such cases they form both the foot and hanging walls of the ore body. But the ore-bearing chert formation is always associated with black carbonaceous slates, which constitute the base on which the ore-bearing formation rests. In the Youngstown mine 3 feet of so-called "graphite" was passed through before the usual carbonaceous slates were reached.[1] The hanging wall is also carbonaceous slate. At places thin quartzitic beds which approach a true quartzite are associated with the slate.

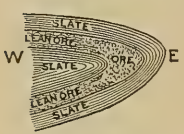


FIG. 14.—Sketch to illustrate the occurrence of ore bodies.

The ores occur in the cherts in pockets and lenticular masses, which always agree in greater dimensions with the strike of the beds with which they are associated. The lenticular character is well shown in the Dunn, Columbia, and Great Western mines. In the Dunn mine the bodies overlap. In the Great Western mine in 1887 seven different ore bodies in an east-west line, separated by areas of barren rock, mostly slate, were being mined. In following these isolated ore bodies to the east, at various places they are found to turn around a horse of rock. Their occurrence is illustrated by the horizontal section, fig. 14. Evidently the ore bodies accumulated in westward-pitching synclinal troughs, in which the hanging wall appears to the miners as a horse of rock.

The ore bodies in general pitch to the west at varying angles corre-

[1] This information was furnished by Mr. C. T. Roberts, of Crystal Falls. It was not possible to obtain a specimen of the graphite for examination.

sponding to the pitches of the axes of the synclines in which they occur. The pitches of these folds in turn correspond to the westward pitch of the Crystal Falls synclinorium, of which the secondary synclines containing the ore bodies are a part. A typical example of the occurrence is shown in the Armenia mine ore body, which is found, according to Van Hise, "at the bottom and on the sides of a synclinal trough, pitching at an angle of about 45°."[1] The trend of the axis is to the south and west.

The dip of the ore bodies is always steep, and generally to the south, but varies in places to a few degrees north.

ORIGIN.

The fact that the important mines in the district are located in a synclinal basin and that they all possess an impervious footwall of black slate gives very clearly the reason for their existence and indicates their mode of origin. They are concentrates in synclinal troughs.

In the Marquette and Penokee-Gogebic districts the ore bodies are frequently found associated with dikes of dolerite (diabase), which have been altered to "diorite"-schists, and so-called soapstone or paint rock.[2] Only one such association is known for the Crystal Falls district. Wadsworth mentions having seen a dike in the Paint River mine.[3]

In the field notes of the Lake Superior survey for 1891, I find the statement made that "the strata of the ore formation, which here strikes nearly east and west, is cut by an eruptive dike which runs about northwest and southeast. This dike hades to the west, and forms with the hanging slates of the ore formation a trough pitching to the west at a very steep angle. In this trough is situated the ore body upon which the Paint River and the Monitor[4] mines are working." This ore body is stated to be about 100 feet wide, 300 feet long, and of unknown depth. When I was in the district, the mines were closed, or only shipping from stock piles, so that I had no opportunity of verifying this observation. From this statement it appears that in this particular case the ore is due to the presence of

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[1] Iron ores of the Marquette district of Michigan, by C. R. Van Hise: Am. Jour. Sci., 3d series, Vol. XLIII, 1892, pp. 130.

[2] Merriam also mentions in his notes a dolerite dike found cutting the ferruginous rocks at the Glidden exploration. In this case it does not appear that an ore body was formed.

[3] Sketch of the geology of the iron, gold, and copper districts of Michigan, by M. E. Wadsworth: Rept. State Board of Geol. Survey for 1891–92, 1893, p. 108.

[4] Now known as Lamont mine.

this dike, as it occurs in a pitching trough, formed by its junction with the impervious slate. These same relations are well known to be the cause of similar occurrences in the Lake Superior districts above mentioned.

The original rock from which the ores were formed was cherty iron carbonate, which in many places is found associated with the iron-bearing formation. The cherty carbonate shows the various stages of alteration from the compact cherty siderite to the banded ore and chert rocks which form the nuclei for the addition of the iron obtained from the higher extensions of the beds. Percolating waters have been the agents in this process of replacement and concentration. Consequently where the rocks have been most shattered, we find the water was especially active. Hence it is, also, that we find the deposits in this closely folded part of the Upper Huronian.

As to the origin of the cherty carbonate itself, we know nothing definite. Its association with the carbonaceous slates would indicate the agency of organic matter in its production, possibly in some such manner as is rather generally accepted for the formation of the Carboniferous carbonate ores. The Upper Huronian ores, as well as the Lower Huronian, are supposed to have been formed in this same way, and from the same kind of rock. Under the discussion of the Lower Huronian ores (p. 70) these points were discussed more in detail, and references given to the literature, and the reader is referred to that discussion for further details.

SIZE OF THE ORE BODIES.

No definite general statement can be made as to the size of the ore bodies, as this varies considerably. None of the bodies which are being worked, so far as I can learn, are less than 30 feet wide. In one of the old mines crosscuts disclosed a width of nearly 200 feet. This same ore body is reported to be at least one-fourth of a mile long.

METHODS OF MINING.

The first development of the iron ores of this district was by the stripping and open-cut method, very few resorting at once to under-ground work. Nearly two-thirds of the product of certain of the mines has been from open-pit work. When the open pits become too deep to be readily worked as such, shafts are sunk and the exploiting of the ore body is carried on under ground, at times both open-pit and under-ground work being carried on simultaneously. The Mastodon presented the unusual

sight of an open pit extending down 200 feet, part of the workings still being roofed over by an enormous arch of rock. All work in the district is at present under ground.[1] As a rule, the under-ground work has not, thus far, been carried to very great depth, the two deepest mines being the Great Western and the Dunn, which are down, respectively, 700 and 720 feet. The others are down to depths varying from 100 to 450 feet, the lowest figures being, as a rule, for the youngest mines, the more important ones having nearly reached the 400-foot level or passed beyond it.

In the early mining days of the district an extensive system of timbering was resorted to, but gradually, as the cost of timber increased and this item became burdensome, careful attention was paid to this point, and, where practicable, the system of caving or the system of filling was introduced (Mastodon). At the present time most, if not all, of the important producers are mined with open stopes, pillars being left only when necessary. From this it would appear that the rocks had not been much broken, but it should be borne in mind that the ore deposits themselves are later than the folding, and in the process of their formation many of the cracks in the surrounding beds could have been filled with ore or other material and the rocks thus quite rigidly united again. That cementation has taken place is evident from an examination of almost any hand specimen or slide, where one may see veins of infiltrated quartz traversing them at various angles. The extremely wet character of the Great Western would seem to indicate that locally the rocks may still be very much fissured.

PROSPECTING.

Owing to the impossibility, with our present knowledge, of mapping the various beds of the Upper Huronian, it is not possible to give any directions with reference to the exact lines which should be followed in searching for ore. However, since the areas which are underlain by igneous rocks have been delimited, there is no longer any excuse for wasting time and money in prospecting in these unpromising portions of the district. Where indications point to considerable rock movements, and where the sideritic rocks are found associated with impervious slates, explorations are warranted.

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[1] This was written in 1896. Since then a large part of the Mansfield ore body has been stripped, and this may be worked at present by open-cut methods.

PRODUCTION OF ORE FROM THE CRYSTAL FALLS AREA.

In the following table the first column contains the names of the mines or combinations of mines of the Crystal Falls area. These are arranged alphabetically for ease of reference, and not according to date of opening or amount of ore produced, as is so usually the case. In one case, that of the Claire mine, the mine was operated by the company operating the Youngstown, and its output accredited to that mine until 1891, when the two mines were separated. Following the name under which a mine is known at present, there is given in parentheses in chronological order the name or names by which the mines were formerly known. The second column gives the location of the mine. Following these data there are arranged in columns the yearly shipments from the time of the first opening to the closing of the mines, or to January 1, 1899. In many cases the ore body had been definitely located and considerable work done and ore accumulated upon stock piles several years before the first shipments were made, but it would be impossible to give the exact date of the opening of the mine unless we considered the year of first shipment as such. In a column following the yearly shipment the total shipment for each mine is given. This is followed by a column giving the year in which the maximum shipment was made, and by another giving the amount of this shipment. In the horizontal column at the foot of the page may be found the total shipments for each year and the total product of the district since its first exploitation. The figures for the district have been obtained either by correspondence with the mining companies or from the annual reports of the commissioner of mineral statistics of Michigan. Acknowledgments are due to certain of the companies which have, through their managers, been very obliging in furnishing information concerning the mines they operated.

From a comparison of the total shipment of the area for 1898 with the total shipment of the Menominee range 2,522,265 long tons and of the entire Lake Superior region 14,024,673 long tons for the year, it will be seen that the Crystal Falls area furnished 13 per cent of the total iron-ore shipment of the range and 2⅓ per cent of the region.[1]

[1] Total shipments for 1898 were obtained through Mr. John Birkinbine from the Iron Trade Review.

IRON-ORE SHIPMENTS OF THE WESTERN HALF OF THE

ation.	Operated by—	1882	1883	1884	1885	1886
.33 W						
R. 32 W	Claire Mining Co					
., R. 32 W	Huron Iron Co	15, 940	4. 334	6, 774		14, 282
W		1, 341				
R. 32 W	Corrigan, McKinney & Co					
, R. 33 W			3. 410	508	9, 843	17, 684
R. 33 W	Dunn Iron Mining Co					
, R. 32 W	Iron Star Co	587	22, 825	20, 722		25, 725
R. 33 W	Pickands, Mather & Co					
., R. 32 W						
R. 32 W						
.43 N., R. 32 W	Lamont Iron Co					
R. 32 W						
R. 32 W	Lincoln Mining Co	8, 131	453			
R. 33 W						
., R. 31 W	De Soto Mining Co					
R. 33 W	Mastodon Iron Co	3, 477	18, 577	18. 020	11, 737	41, 640
R. 33 W	Michigan Exploring Co					
R. 32 W	Paint River Iron Co	6, 515	5, 973	11, 652	2, 373	13, 933
., R. 32 W	Illinois Steel Co	6, 198	15, 292	8, 343		25, 638
		42, 189	70, 864	66. 019	23, 953	138, 902

* Previous to 1891 Claire and Youngstown products were quoted t

† Lower Huronian. Only productive Bessemer mine in Crystal Fa

TAL FALLS DISTRICT, GIVEN IN TONS OF 2,240 POUNDS.

1888	1889	1890	1891	1892	1893	1894	1895	1896	1897	1898
....	47,775	26,649	....	....	....	....	2,045	....	....	....
....	....	....	55,000	57,351	9,612	....	....	....	....	....
10,936	11,385	60,133	70,770	57,682	22,426	10,300	70,867	87,202	24,623	14,199
....	....	....	....	....	....	....	....	....	....	....
....	....	3,975	....	....	....	....	14,387	44,526	95,210	128,233
....	....	....	....	....	....	....	....	....	....	....
118,091	151,828	156,953	162,721	133,945	58,261	....	90,886	47,081	31,062	49,381
21,861	38,451	71,719	62,464	87,487	661	....	....	....	....	....
....	....	....	35,531	65,459	11,323	....	1,046	95,767	96,032	69,865
....	....	2,020	1,057	1,021	....	....	....	....	....	....
....	....	....	....	15,543	2,275	....	....	....	....	....
2,690	21,620	31,139	26,226	42,819	13,777	2,600	....	....	....	....
....	....	....	....	2,844	....	....	....	....	....	....
....	....	....	1,813	26,020	8,757	....	....	....	....	....
2,722	4,006	1,476	....	....	....	....	....	....	....	....
....	....	18,303	49,836	69,259	69,558	....	....	....	39,012	60,877
51,293	63,086	66,559	45,370	9,150	23,485	....	23,781	....	....	....
....	....	....	....	....	505	....	1,071	....	216	....
12,506	32,700	62,654	45,435	18,390	....	....	....	....	....	....
12,700	7,471	44,460	3,705	....	....	....	13	....	661	....
232,799	378,322	546,040	559,828	586,970	220,640	12,900	134,096	274,576	286,816	322,555

l credited to Youngstown, though they were about equally divided.

IRON-ORE SHIPMENTS OF THE WESTERN HALF OF THE CRYSTAL FALLS DISTRICT, GIVEN IN TONS OF 2,240 POUNDS.

Name of mine	Location	Operated by—	1882	1883	1884	1885	1886	1887	1888	1889	1890	1891	1892	1893	1894	1895	1896	1897	1898	Total shipment of individual mines and of district to date.	Year of maximum shipment.	Amount of shipment.	Name of mine.
Armenia (Smith)	E. ½ SE. ¼ sec. 23, T. 43 N., R. 33 W.									47,775	26,649					2,045				76,469	1889	47,775	Armenia (Smith).
Claire*	NE. ¼ SE. ¼ sec. 19, T. 43 N., R. 32 W.	Claire Mining Co.										55,000	57,351	9,612						121,963	1892	57,351	Claire.*
Columbia (1. Union; 2. Sheldon & Schafer)	NW. ¼ NW. ¼ sec. 31, T. 43 N., R. 32 W.	Huron Iron Co.	15,940	4,334	6,774		[illegible]	[illegible]	[illegible]	11,385	60,133	70,770	57,682	22,426	10,300	70,867	87,202	24,623	14,199	481,190	1896	87,202	Columbia (1. Union; 2. Sheldon & Schafer).
Crystal Falls	Lot 3, sec. 20, T. 43 N., R. 32 W.		1,341																	1,341	1882	1,341	Crystal Falls.
Crystal Falls	SE. ¼ NE. ¼ sec. 21, T. 43 N., R. 32 W.	Corrigan, McKinney & Co.									3,975					14,387	44,526	95,210	128,233	286,331	1898	128,233	Crystal Falls.
Delphic	NE. ¼ SW. ¼ sec. 24, T. 42 N., R. 33 W.			3,410	508	9,843	17,684	[illegible]												33,246	1886	17,684	Delphic.
Dunn	NW. ¼ NE. ¼ sec. 1, T. 42 N., R. 34 W.	Dunn Iron Mining Co.						[illegible]	[illegible]	151,628	156,953	162,721	133,945	58,261		90,886	47,081	31,062	49,381	1,025,679	1891	162,721	Dunn.
Great Western (Iron Star)	NE. ¼ SW. ¼ sec. 21, T. 43 N., R. 32 W.	Iron Star Co.	587	22,825	20,722		[illegible]	[illegible]	[illegible]	38,451	71,719	62,464	87,487	661						375,742	1892	87,487	Great Western (Iron Star).
Hemlock	NW. ¼ SW. ¼ sec. 4, T. 44 N., R. 33 W.	Pickands, Mather & Co.										35,531	65,459	11,323		1,046	95,767	96,052	69,865	375,043	1897	96,052	Hemlock.
Hollister	NW. ¼ SW. ¼ sec. 13, T. 43 N., R. 32 W.										2,020	1,057	1,021							4,098	1890	2,020	Hollister.
Hope (1. Blaney; 2. Wauneta)	NE. ¼ SE. ¼ sec. 27, T. 43 N., R. 32 W.												15,543	2,275						17,818	1892	15,543	Hope (1. Blaney; 2. Wauneta).
Lamont (Monitor)	Lot 6, NW. ¼ SE. ¼ sec. 20, T. 43 N., R. 32 W.	Lamont Iron Co.							[illegible]	21,620	31,139	26,226	42,819	13,777	2,600					140,871	1892	42,819	Lamont (Monitor).
Lee Peck	W. ½ NE. ¼ sec. 20, T. 43 N., R. 32 W.												2,844							2,844	1892	2,844	Lee Peck.
Lincoln (Fairbanks)	W. ½ SW. ¼ sec. 21, T. 43 N., R. 32 W.	Lincoln Mining Co.	8,131	453								1,813	26,020	8,757						45,174	1892	26,020	Lincoln (Fairbanks).
Manhattan (South Mastodon)	NE. ¼ SE. ¼ sec. 13, T. 42 N., R. 33 W.								[illegible]	4,066	1,476									8,204	1889	4,066	Manhattan (South Mastodon).
Mansfield (Caledonia)†	NW. ¼ NW. ¼ sec. 20, T. 43 N., R. 31 W.	De Soto Mining Co.									18,303	49,836	69,259	69,558				39,012	60,877	306,845	1893	69,558	Mansfield (Caledonia).†
Mastodon	SE. ¼ NE. ¼ sec. 13, T. 42 N., R. 33 W.	Mastodon Iron Co.	3,477	18,577	18,020	11,737	41,040	[illegible]	31,293	63,086	66,559	45,370	9,150	23,485		23,781				425,290	1890	66,559	Mastodon.
Michigan	NE. ¼ NW. ¼ sec. 9, T. 44 N., R. 33 W.	Michigan Exploring Co.												505		1,071		216		1,792	1895	1,071	Michigan.
Paint River	NE. ¼ SE. ¼ sec. 20, T. 43 N., R. 32 W.	Paint River Iron Co.	6,515	5,973	11,652	2,373	13,933	[illegible]	12,306	32,700	62,654	45,435	18,390							222,371	1890	62,654	Paint River.
Youngstown	NW. ¼ SW. ¼ sec. 20, T. 43 N., R. 32 W.	Illinois Steel Co.	6,198	15,292	8,343		25,658	[illegible]	12,700	7,471	44,460	3,705				13		661		158,899	1890	44,460	Youngstown.
Total			42,189	70,864	66,019	23,953	[illegible]	[illegible]	[illegible]	378,322	546,040	559,828	586,970	220,640	12,900	134,096	274,576	286,816	322,555	4,036,448			Total.

* Previous to 1891 Claire and Youngstown products were quoted together [illegible] to Youngstown, though they were about equally divided.

† Lower Huronian. Only productive Bessemer mine in Crystal Falls area.

CHAPTER VI.

THE INTRUSIVES.

Under this general head there is here included an extremely varied assortment of rocks exhibiting in common intrusive relations to sedimentary and igneous rocks. This division is here used merely because it simplifies the classification of the rocks of the district, and the term "intrusives" is not to be interpreted as synonymous with the "dike rocks" (ganggesteine) of some authors, a petrographical division which, in the opinion of the writer, is not warranted.

These intrusive rocks differ very materially in field occurrence, petrographically, and in point of age from the igneous rocks thus far described. In age much younger than the volcanics, they still bear a close resemblance to some of them; indeed, some forms are identical in character. Massive granular rocks are the common forms. Porphyritic varieties are very subordinate.

The rocks are all considered as intrusives into either the Lower or the Upper Huronian. In most cases the intrusive relations may be said to be rather inferred than demonstrated, for the direct contacts have been observed in very few cases. However, where isolated sets of knobs of eruptive rocks are found in areas, the greater portion of which are underlain by sedimentaries, the natural inference is that they penetrate these sedimentaries. Where isolated sets of knobs are composed of the same kind of rock or show variations of the same type, they may be presumed to be connected. For the most part the dikes and bosses are too small to admit of indication upon the accompanying map. Wherever their size has warranted it, they have been represented, as in the case of the acid intrusives between the Paint and Michigamme rivers, and of the basic intrusives north of Crystal Falls.

ORDER OF TREATMENT.

For the sake of convenience and to avoid repetition, the age of the intrusives as a whole is first determined, and then follows a brief description of the effect of the folding of the district on the distribution of the eruptives.

The rocks described have been divided into those of acid, basic, and ultrabasic composition, and the usual order of discussion from the acid to the basic will be followed. In Section I rocks are described which are geologically disconnected. In Section II is a description of a series of rocks which constitute a geological unit, and are especially interesting from a petrogenetic standpoint. Here also the order of discussion is from the acid to the basic. The geographical distribution of the rock of each division is given, only those outcrops being accurately located which are of very large size or which for other reasons are of special interest from a stratigraphical or a petrological standpoint.

After the petrographical description of each of the rocks a statement will be made of its field relation to the adjacent rocks, if its relations have been discovered. This will be followed by a brief account, in those rare cases in which a contact has been observed, of the metamorphic action which it has caused in the sediments through which it was forced.

AGE OF THE INTRUSIVES.

The intrusives have forced their way through the Lower and Upper Huronian sedimentaries, but have never been found to penetrate the horizontal Lake Superior (Cambrian) sandstone. These facts alone are conclusive proof that their period of intrusion falls in the time which elapsed between the deposition of the Upper Huronian and that of the Cambrian.

In the discussion of the time of the folding of the Upper Huronian the conclusion was reached that this folding preceded the deposition of the Keweenawan series. If the intrusives to be described had existed at the time of folding, they must certainly have suffered from the orogenic movements. Examination of the exposures of the intrusives has not shown schistose masses, nor has detailed microscopical study disclosed the cataclastic textures which accompany powerful dynamic movements, except in one case, which is described on p. 194, and is presumed to be due to purely local movements. Such being the facts, the conclusion follows that the intrusives were intro-

duced subsequent to the folding of the Upper Huronian, or are of Keweenawan or post-Keweenawan age.

A closer approximation to the age of the intrusives is not possible, unless we rely upon petrographical similarity. The dolerites of the Crystal Falls district are similar to those forming the flows and dikes of the Keweenawan on Keweenaw Point. They are also similar to the basic intrusives of the Marquette district, with which this is practically a geological unit, and likewise they agree petrographically with the dolerite dikes of the Penokee-Gogebic district. In both districts the late intrusives have been considered to be of Keweenawan age.[1] Rominger,[2] in his report for 1881 and 1884, calls attention in a general statement to the possible connection of the doleritic dikes penetrating the Michigan Huronian with the flows and dikes of the "Copper-bearing formation" (Keweenawan).

While correlation by means of petrographical similarity would not hold for widely separated areas, it seems to be well worth considering for areas which are so closely connected as are the iron districts of the Upper Peninsula of Michigan.

Judging from the evidence thus presented, the dolerites of the Crystal Falls area are probably contemporaneous with the intrusions of the Penokee-Gogebic and Marquette districts and with the volcanics of Keweenawan time.

RELATIONS OF FOLDING AND THE DISTRIBUTION OF THE INTRUSIVES.

In the preceding chapter, in the sections on folding of the Upper Huronian, p. 158, it was shown that the main folds of the district follow an approximately northwest-southeast course, and that upon these were superimposed minor folds approximately at right angles to these. The lines of weakness parallel to the axes of the main folds have been taken advantage of by certain of the intrusives, especially the dolerites.

A glance at the general map (Pl. III) shows that the dolerite dikes which have been traced for considerable distances—that is, are more than great knobs uncovered by erosion—have a northwest-southeast trend, in agreement with the general direction of the major folding of the district.

[1] Mon. U. S. Geol. Survey, Vol. XIX, p. 349; Vol. XXVIII, p. 218.
[2] Geol. of Mich., Vol. V, cit., p. 6.

The only apparent exception is that part of the great mass in T. 43 N., R. 31 W., which extends north and south along the Michigamme River; but this is really not an exception, since the folds of the Mansfield slates here run in the same direction.

SECTION I.—UNRELATED INTRUSIVES.

CLASSIFICATION.

Under the above heading are included intrusive rocks which occur in such isolated outcrops that no definite relations can be shown to exist between them and other igneous rocks of similar or related characters.

The intrusives described under this heading comprise rocks of acid, basic, and ultrabasic composition, represented respectively by the granites, the dolerites and basalts, and the picrite-porphyries.

ACID INTRUSIVES.

The acid intrusive rocks may be divided into ordinary biotite-granite (granitite) with a micropegmatitic variety, and muscovite-biotite-granite and rhyolite-porphyry.

GEOGRAPHICAL DISTRIBUTION AND EXPOSURES OF GRANITES.

The biotite-granite proper does not occur in the district in large quantity. It is found in dikes penetrating the Upper Huronian rocks in secs. 15 and 22, T. 42 N., R. 31 W., and in dikes, cutting diorite intrusives in the Upper Huronian, in sec. 22, T. 42 N., R. 31 W.

The micropegmatitic variety of the biotite-granite is confined to an area underlain by the Lower Huronian rocks. It occurs at N. 750, W. 740, sec. 17, T. 43 N., R. 31 W., and N. 1750, W. 1580, sec. 29, T. 43 N., R. 31 W., in small quantities in isolated dikes, cutting the dolerites which penetrate the Lower Huronian series.

Owing to their small size, none of the above-mentioned exposures are represented on the maps.

The muscovite-biotite-granite forms large, bold, isolated knobs in secs. 19, 20, 29, and 30, T. 42 N., R. 31 W., between the Paint and Michigamme rivers. These knobs are so closely related petrographically that they are presumed to represent a large boss, and they are therefore represented as a unit on the geological map of the district, Pl. III. Other smaller areas of granite occur and are shown on the detail map, Pl. XVIII.

BIOTITE-GRANITE.

The biotite-granites vary in color from light reddish-brown to dark-gray and greenish rocks, and in grain from fine to coarse. The structure ordinarily is that of a normal granite. In some of them the micropegmatitic intergrowth of quartz and feldspar may be observed in small quantity. In others this forms the characteristic part of the rock, and these rocks may be properly termed micropegmatitic granites. In most of the sections the usual constituents in ordinary proportions occur.

In all the rocks the main mass of the quartz forms irregular grains, molded on the other constituents. Sometimes round areas of quartz are included in the feldspars. The quartz contains very commonly, and usually in great quantities, liquid inclusions with dancing as well as stationary bubbles.

The feldspar is nearly always of two kinds—orthoclase and plagioclase. Microcline was also observed, but in neglectable quantity. These feldspars in the great majority of slides show fairly good rectangular outlines, and in some cases these are strikingly well developed. In some slides the plagioclase is observed in rectangular crystals and the orthoclase is found in large irregular plates which are molded on the plagioclase, showing conclusively their relative age. The plagioclase is finely twinned according to the albite law, and also in some slides exhibits pericline twinning. A case was observed in which two crystals, one showing albite twinning, the other both albite and pericline twinning, were grown together so as to correspond to the Carlsbad twins of orthoclase. The plagioclase gives low extinction angles, which show it to be rather acid. The amount of plagioclase in some of the sections—for example, in those of the numerous small dikes cutting the schists near Norway portage in sec. 15, T. 42 N., R. 31 W., and the one cutting the gabbro at the SE. corner of sec. 22, T. 42 N., R. 31 W.—is very large, denoting an increase in soda and lime and indicating a relationship to the diorites. The geological relations are not such, however, as to enable this connection to be shown in default of chemical analyses.

The orthoclase is for the most part untwinned, or else shows simple Carlsbad twinning. In some sections the feldspars are quite fresh, but in others they are seen to be opaque, porcelain-like, and in still others the

original feldspar material is almost entirely replaced by a mass of muscovite, with some little epidote-zoisite and biotite. The muscovite in these secondary aggregates gives excellent though small rectangular sections, showing its fine cleavage very distinctly. Well-determinable kaolin flakes were not found.

The mica is well represented by both biotite and muscovite. Both occur in very well developed crystals, the muscovite showing the most perfect development. The biotite has partly altered to chlorite, with a simultaneous production of rutile, sagenite, and sphene. Between the chlorite laminæ one frequently sees lenticular areas of secondary calcite. Quite commonly the sagenite is found included in these areas.

In only one specimen was hornblende observed. This was from a granite dike which cut the dolerite. The hornblende is of a noncompact variety, which upon the edges is finely fibrous. It corresponds exactly to that which is found in the adjacent dolerite.

The contact between the granite and dolerite appears irregular, as though the dolerite had been to some extent broken. As the contact is approached from the granite side the hornblende increases in quantity. It is thought probable that the hornblende in the granite along the contact is secondary after pyroxene, and that this pyroxene was obtained by the inclusion of fragments of the dolerite.

Accessory minerals are not present in large quantity.

Iron oxide is not present in great quantity, and when seen it is usually titaniferous, as rutile is found as an alteration product. In one case the hexagonal plates show the presence of ilmenite. Apatite is rare, as a rule, though occurring in some sections in considerable quantity. Zircon is scarce, as are also sphene and rutile. Epidote is rather common. In some cases it is seen in biotite surrounded by a pleochroic halo, and in such cases it is probably original. The secondary minerals, muscovite, biotite, chlorite, epidote, sphene, rutile, and calcite, show their usual characters. Calcite is abundant, and is more or less ferruginous. It is found in rhombohedra and also in irregular masses. In all cases its secondary origin is clear.

MICROPEGMATITES.

The micropegmatitic varieties of the biotite-granite show the same variations in color, from reddish to gray and greenish, and in grain from

fine to medium, as do the biotite-granites proper. In general they may be described as biotite-granites in which the micropegmatitic intergrowth of quartz and feldspar instead of being subordinate preponderates. Many of the well-crystallized feldspars are surrounded by a border of micropegmatite, which varies from a narrow strip to a very wide border, usually in inverse ratio to the size of the feldspar nucleus. The feldspar in the intergrowth is continuous with that of the nucleus. A coarsely radial arrangement of the micropegmatitic intergrowth was frequently observed. Where the feldspars and quartz are predominantly porphyritic, and micropegmatite forms the groundmass, the rock grades over into the rhyolite-porphyries with micropegmatitic groundmass—the inappropriately named granophyres of Rosenbusch.

The biotite of the micropegmatitic granites has partly altered to chlorite and sagenite. In some of these rocks the biotite is collected into large aggregates of imperfect individuals, which surround large pieces of iron ore. In some instances it is included in the plagioclase. The biotite flakes in the feldspar are sometimes so numerous as to conceal almost completely the feldspar substance. In one instance the feldspar of such a micropegmatitic intergrowth is completely replaced by biotite. These secondary biotite flakes surrounding the remaining more or less rounded quartz areas of the micropegmatite produce a rock which is strikingly like a mica-schist in places, although it is of unquestionably eruptive character.

Tourmaline is a rare accessory in these granites, a small smoke-brown crystal having been observed in one section. Titaniferous iron ore altering to leucoxene or sphene and rutile is found, as are also the common accessory minerals—apatite, rutile, and zircon. They contain also the same secondary minerals as the normal biotite-granite.

MUSCOVITE-BIOTITE-GRANITE.

These are medium-grained rocks, and, owing to the fact that the muscovite is more abundant than the biotite, have a light-gray color.

The muscovite is noticeably automorphic with respect to the biotite, though the biotite is also in well-developed automorphic plates. Plagioclase is present in these granites in very large quantity. It shows an excellent zonal development, with diminishing angle of extinction—that is, increasing acidity—from the center outward. The center of the individuals

is nearly always extensively altered, while the outer zones are comparatively fresh. A maximum extinction angle of 15° against the twinning planes in the zone perpendicular to 010 was observed on an unaltered zone surrounding an altered core. This would indicate the feldspar to be perhaps as basic as labradorite at the center. The other essential minerals, quartz and orthoclase, occur in usual quantity and show nothing of especial interest. Sphene and apatite are the only accessory minerals present. An apatite crystal was observed which was included in quartz, and contained the brown apparently vitreous core so frequently seen in the apatites of basic rocks. Where included in biotite, it is surrounded by a pleochroic halo.

No analyses were obtained of these granites, but from the quantity and character of the feldspar as noted above, these rocks are thought to be closely related to dioritic rocks. Indeed, it is a question if they should not be classed as quartz-diorites.

RELATIONS OF GRANITES TO OTHER INTRUSIVES.

In two cases already mentioned granite dikes cut the diorites. Granite also cuts the gabbro, and dikes of granite were observed penetrating the dolerites, thus indicating that the granites are younger than these igneous rocks.

DYNAMIC ACTION IN GRANITES.

An examination of the granites with particular reference to pressure phenomena shows that they exhibit a great difference in this respect. Some show scarcely any traces of pressure, while others quite closely associated may have been affected thereby to such an extent that a more or less strongly wavy extinction of their mineral constituents is general. However, but a single instance of a supposed granite possessing an excellent cataclastic structure and imperfect schistosity was observed, and this rock was so extremely altered as to render doubtful a determination of its original character.

CONTACTS OF GRANITES AND SEDIMENTARIES.

The largest intrusive granite mass is found between the Paint and Michigamme rivers, in secs. 19, 20, 29, and 30, in T. 42 N., R. 31 W. The granite is a muscovite-biotite-granite. The sedimentaries are micaceous graywackes, which have been described on p. 170. Let it suffice

here to repeat that they have been much mashed and recrystallized, but that some of them still show their fragmental origin. New biotite, muscovite, feldspar, and quartz have developed. Where most altered, they are mica-schists and mica-gneisses. These changes are presumed to be due, for the most part, to the orogenic forces which were active prior to the intrusion of the granite (p. 170). If such be the case, the granite began its metamorphic action upon a rock already greatly changed from its original condition.

EVIDENCE OF INTRUSION.

The intrusive character of this large mass of granite is indicated by its stratigraphical position, and is further confirmed by the mechanical effects produced by the intrusion of the granite upon the sedimentaries, by the contact effects produced in the sediments, and by the presence in the sedimentaries of granite dikes forming offshoots from the main mass.

The mechanical effects are well shown by the inclusion of sedimentary fragments and by the dislocation and folding of the beds. Inclusions are rather common and are usually of considerable size.

The dislocation and folding are beautifully shown at N. 1970, W. 570 paces, sec. 30, T. 42 N., R. 31 W. In general the layers in the graywacke, which are alternately rich and poor in mica, strike N. 15° to 30° W., but where the intrusives are, these layers are found to strike almost due north and south. At the above location the beds are folded into small, closely-compressed anticlines and synclines, which plunge to the east at an angle of about 80°. At this place the micaceous graywacke is broken into small pieces, which are thoroughly injected and cemented by the granite, thus forming a typical eruptive breccia. The granite cement is microgranitic, with comparatively little quartz and a small amount of chloritized mica. The fragments of micaceous graywacke in the breccia appear to be rather more feldspathic than usual, but otherwise seem not to have been much affected.

Owing to the altered condition of the sediments prior to the granite intrusion, and to the alternation of sediments of somewhat varying character, we can not expect to find such clearly outlined concentric zones surrounding the granite as in cases where the sediments are uniform. In one case a contact was observed between the granites and apparently the main mass of the sediments. Along this line of contact biotite and white

mica have developed in great abundance. Mica is well known as one of the minerals produced in granite contacts, and it evidently here owes its abundance to the presence of the granite.

At a considerable distance from the nearest intrusive outcrop (2 miles) a mica-schist was observed which was characterized by numerous small but prominent nodules that stood out upon its weathered surface. The rock contains a considerable quantity of an apparently original chlorite in large automorphic plates. The nodules were produced by large individuals of staurolite. The staurolite has almost completely altered, remnants only of the original individuals remaining. These remaining grains show a very poor cleavage, and extinguish parallel to it. These include blebs of quartz and particles of iron oxide. They have the usual pleochroism for staurolite, varying from golden yellow for $\mathfrak{c}$ to yellowish white for $\mathfrak{a}$ and $\mathfrak{b}$. The alteration products in which the grains lie are fine scaly aggregates of minute leaves of muscovite, with here and there larger plates of the same mineral. A few grains of quartz and a small amount of iron oxide, possibly partly original, are found in the mass. This observation of the alteration of the staurolite to muscovite confirms the observations of Thürach[1] and Pichler.[2] A similar staurolitiferous mica-schist, occurring in the same locality, was described by C. E. Wright for the Wisconsin survey.[3] On these particular specimens the characteristic twins of staurolite may be observed macroscopically as well as in thin section. Wright has also described a garnetiferous mica-schist from this area of metamorphic schists.[4] Both of these schists contain prisms of bluish tourmaline in considerable quantity.

It appears highly probable that these staurolitiferous and garnetiferous schists owe their origin to the intrusion of the igneous rocks, though no well-marked contact zones could be outlined.

The exomorphic contact effect of the granite is more noticeable where a large body of the granite contains a sedimentary intrusion than elsewhere.

The determination of the sedimentary origin of the fragments included in the granite is based primarily upon the probability that in its passage

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[1] Thürach, Groth's Zeitschr., Vol. II, p. 423.

[2] A. Pichler, Beiträge zur Mineralogie Tirols, Neues Jahrb., 1871, p. 54.

[3] Geology of the Menominee iron region, by C. E. Wright: Geol. of Wisconsin, Vol. III, 1878, Part 8, p. 695.

[4] Loc. cit., p. 695.

through the sedimentary rocks which now surround it the granite included fragments of them.

In addition to this a well-defined banding is still present in these fragments. Though by no means conclusive evidence, this is considered as an indication of their having been originally deposited through the mediation of water. The sediments have been completely recrystallized into fine-grained mica-gneisses.

The sedimentary fragments included in the granite now show the following characters. They are composed of layers of two kinds. The one kind of layer is very fine grained, of gray color, and consists predominantly of biotite in fairly good automorphic plates, muscovite in small quantity—but in automorphic plates—even with respect to the biotite, feldspar, quartz, and iron oxide. The feldspar is in small equidimensional grains. Only one finely striated feldspar was observed, the greater part possibly being orthoclase. It shows in places a well-developed zonal structure, the zones conforming to the outlines of the grains. The zonal structure probably depends upon varying quantities of the soda and potash molecule. Quartz occurs in grains in very small quantity.

The second kind of layer which is seen in the fragments is much coarser grained than is the first, just described, and is very much darker. It is composed mainly of muscovite and biotite, in about equal quantities, feldspar, quartz, magnetite, and ilmenite, with some tourmaline. Both feldspar and quartz occur in grains, the former in small quantity. The biotite is in small plates less well developed than the muscovite, though mostly automorphic. It is partly bleached and has associated with it here and there some secondary epidote. The muscovite is in very large automorphic plates, some of them twinned according to Tschermak's law, and includes flakes of biotite and grains of quartz and feldspar. This gneiss contains also a large number of crystals of tourmaline, showing strong dichroism from light pinkish to dark grayish blue. Iron oxide is present, both as magnetite and as ilmenite. The quadratic individuals of the one and the hexagonal plates of the other at times are very well developed. No signs of pressure whatsoever are seen.

The muscovites evidently represent the last product of crystallization, as shown by their including all the minerals which had been previously formed. (Fig. *A*, Pl. XXXIV.) These muscovites are probably to be

looked upon as the product of mineralizers, dependent upon the presence of the hot granite injection, to whose action may also be referred the presence of the tourmaline.

The line of contact between the granite and the sedimentary fragments, though somewhat irregular, is macroscopically very well defined by the difference in size of the mineral constituents of the two rocks. Here and there in the fragments there are seen thin masses of the granite which were injected along the planes of sedimentation, and also traverse cracks penetrating the sediments. On the granite side of such a contact there is a narrow zone very noticeably richer in large biotite flakes than the granite is ordinarily. No difference can be noticed on the sedimentary side of the contact. The microscopical examination of the contact emphasized the endogenous character of the metamorphic action. There is more biotite present than in the normal granite.

The feldspar in the normal granite has a decided tendency toward automorphic development. Where the feldspars of the granite touch the metamorphosed sediments they are partly rounded, and the mica plates developed in the sediments have in general a parallel structure around that side of the feldspar which is turned toward the fragments.

At another point the quartz of the granite, where it comes in contact with the sediments, has developed as an automorphic individual, and looks as though it were pressed into the fragment. The quartz crystal contains near its edge grains of feldspar and flakes of mica, thus making an imperfect narrow poikilitic zone. Beyond this zone there is the sedimentary rock proper, and there the mica plates lie parallel to the contours of the quartz. An illustration of such a contact is shown in figs. *A* and *B*, Pl. XXXV, as seen in ordinary light and also between crossed nicols.

It appears that the formation of the quartz and feldspar noted above caused the arrangement of the constituents of the gneiss parallel to their contours. It would thus seem probable that in this particular case the recrystallization of the original graywacke into the gneiss which we now find in its place followed and was chiefly the result of the intrusion of the granite.

BASIC INTRUSIVES.

The basic intrusives are represented by metadolerites and metabasalts. The dolerites are the most important, and will be treated in detail. Rocks

very similar to the basalts have already been described at length under the Hemlock volcanics, and since they are found in comparatively few dikes they will be passed over with very brief mention.

METADOLERITE.[1]

GEOGRAPHICAL DISTRIBUTION.

The dolerites of the Crystal Falls district for the most part form high ridges extending in a northwest-southeast direction. Their principal occurrence is in the area immediately north, northeast, and east of Crystal Falls. Beginning in secs. 32 and 33, T. 43 N., R. 31 W., there extends a great intrusive mass, varying from a mile to a mile and a half in width, due north to sec. 6, T. 43 N., R. 31 W. There it bends to the northwest, and ends in sec. 3, T. 43 N., R. 32 W. The northwestern extension of this mass is much narrower, never exceeding a half mile, and at many places it is only a few hundred yards in width. In the northern part of T. 42 N., R. 31 W., are a number of knobs which are evidently connected below with these large masses, although the exposures are discontinuous.

A large dike begins in sec. 1, T. 42 N., R. 32 W., and extends for about 5 miles to the northwest into sec. 19, T. 44 N., R. 32 W. This averages about one-eighth of a mile in width, though in places it is three-fourths of a mile wide. Another dike begins in sec. 28, T. 44 N., R. 32 W., and runs for 3½ miles to the northwest into sec. 18, T. 44 N., R. 32 W., and, like the above, is narrow, being only about one-eighth of a mile in average width. A narrow dike less than one-eighth of a mile in width extends in a high ridge from in sec. 16, T. 43 N., R. 32 W., to the northwest for 3 miles and ends in sec. 7 of the same township and range. Numerous isolated knobs occur in T. 44 N., R. 32 W. A small boss is in sec. 24, T. 46 N., R. 33 W., and another at 1,600 paces N., 1,000 W., sec. 19, T. 47 N., R. 33 W.

PETROGRAPHICAL CHARACTERS.

Macroscopical.—The dolerites vary in color from greenish to dark olive-green and almost black. The weathered surface is usually of a very light color, rather a light gray, with frequently a reddish tinge. The texture is

[1] I use the name "dolerite" here merely to indicate the macrostructural difference between the rocks included under it and the fine-grained and aphanitic rocks of the same composition included under the basalts. It is also extended to include *paleo* as well as *neo* eruptives. As nearly all, if not all, the paleodolerites have undergone great alteration, the prefix *meta*—indicating alteration without reference to any specific kind—is very generally applicable.

medium to coarse. Probably the most striking textural characteristic is the peculiar mottled appearance described as "luster-mottling" by Pumpelly,[1] to which the name poikilitic[2] has of late years been more generally applied. This texture is almost always brought out macroscopically on the weathered surfaces by the difference in the weathering of the feldspar and the augite or uralite, these being the prominent mineral constituents of the rock. This poikilitic texture is most common in the coarsest of the metadolerites. In such rocks the augite or uralite areas are of large size, quite commonly 2 centimeters in diameter, and show their mottled character very plainly to the naked eye.

In the medium-grained dolerites the ordinary ophitic texture is predominant, though in these rocks poikilitic areas may be seen. In fact, these poikilitic areas really possess an ophitic texture, according to the definition of that texture by A. Michel Lévy, for the feldspars are developed as laths and the pyroxene is the mesostasis in which the feldspars lie.[3] It is thus clear that, restricting the statement to these dolerites, the ophitic texture is at times included in the poikilitic, and that under such circumstances the two can not be considered as totally different and independent textures, but are, on the contrary, practically identical.

In one dike of dolerite the influence which the conditions of consolidation exert upon the texture is well shown. This dike is only 8 feet wide, but the center is developed as a dolerite, while along the edges where cooling was more rapid, the rock is a porphyritic basalt. The porphyritic texture is caused by the development of pyroxene and feldspar phenocrysts, which lie in a dense basaltic groundmass.

Microscopical.—The original minerals of which the rocks were composed were feldspar, quartz, pyroxene, olivine, biotite (?), apatite, and titanomagnetite. The minerals which are now present in the rocks are for the most part secondary. They are hornblende, muscovite, epidote-zoisite, chlorite, biotite, sphene, leucoxene, calcite, albite, quartz, and iron pyrite. Of these, hornblende is by far the most prominent constituent. A study of the isolated specimens of these rocks might result in their determination as

[1] Metasomatic development of the copper-bearing rocks of Lake Superior, by Raphael Pumpelly: Proc. Am. Acad. Arts Sci., Vol. XIII, 1878, p. 260.

[2] On the use of the terms "poikilitic" and "micropoikilitic" in petrography, by G. H. Williams: Jour. Geol., Vol. I, 1892, pp. 176–179.

[3] Structures et classification des roches éruptives, by A. Michel Lévy, Paris, 1890, p. 30.

uralitic dolerites, epidiorites, or even diorites, as it is impossible, without a sequence of changes, to determine whether the hornblende is original or secondary. Rare rocks contain quartz in sufficient quantity to warrant their designation as quartz-dolerites. However, they differ in no essential respects from the other dolerites. The quartz is in micropegmatitic intergrowth with feldspar, filling the angular interspaces of the rock. These intergrowths were evidently the last elements to crystallize.

The feldspar occurs in large automorphic lath-shaped crystals, which in most cases show polysynthetic twinning. In a few cases unstriated crystals were observed. Owing to the alteration of the feldspar, which has in most cases almost completely destroyed the striations, it has been impossible to make many accurate measurements. Measurements on the zone perpendicular to 010 gave equal extinction angles against twinning planes of 37° as maximum, showing the feldspar to be bytownite. The chief alteration products of the feldspar are epidote and zoisite. With these are usually associated more or less muscovite, some chlorite, and, more rarely, scales of biotite. Accompanying these alteration products one very frequently finds limpid spots of secondary albite or quartz. Some few of the feldspars are smoke-colored, and as the coloring appeared homogeneous even under the highest powers, it would seem to be due to some pigment in the mineral and not to minute inclusions.

Pyroxene is very rare, having been observed in only a few sections and in the majority of these is present merely as small remnants surrounded by its secondary product, uralite. The pyroxene possesses the usual characters of common augite. The augite is quite free from inclusions. Along the edge its alteration to the light-green hornblende, uralite, can be readily followed, and in one case an octagonal basal section of augite was observed which was completely occupied by uralite fibers.

The former presence of olivine is based upon very slight proof, viz, the existence in some of the pyroxene and uralite crystals of areas which are oval or round in shape and are occupied by pilite. The presence of this pilite in the altered augite might possibly be explained as an alteration product of the augite itself, but it is difficult to explain why pilite should develop in one part of the augite and secondary coarse hornblende in the other part. Moreover, the general characters of the rocks are such as to lead one to expect to find olivine present in some of them.

Biotite occurs in large irregular masses which are considered to be primary, as well as in the scales which occur within secondary products of the rock and are considered to be secondary. It is scattered throughout the rocks in irregular pieces, usually associated with iron oxide. Where fairly fresh, it is brown and shows its ordinary character. By weathering it becomes green, having still a high double refraction. By further weathering it passes into a nearly colorless mass that has the faintest tinge of green and scarcely polarizes light. Such masses are crossed by lines of hair-like crystals, some of which intersect one another at angles of 60 degrees, extinguish parallel to their long directions, and show high single and double refraction. These are taken to be rutile. Other crystals, somewhat coarser, also lie irregularly in the biotite masses. They show the same intersections as the rutile. They are very faintly greenish, have a high single and double refraction, are positive in the long direction, and have a maximum extinction angle of 46 degrees. These characters were not sufficient to determine the mineral by, and no other characteristics could be observed.

Ilmenite and titano-magnetite are in irregular grains. These minerals are more or less altered to leucoxene or to sphene. Very frequently the alteration product incloses bands of the iron oxide, which intersect one another at angles of 60 degrees, pointing toward the hexagonal character of the ore. In one case a beautiful example of the alteration of such an ilmenite to rutile was observed. It is exactly similar to that described by Williams in the case of the greenstones of the Menominee district.[1] By low power the mass has a semimetallic luster, and, as it seems to be almost solid, has very much the general appearance of an ore, but by higher power it is resolved into a mass of small golden-brown crystals. These frequently intersect one another at angles approximating 60 degrees (120°), similar to the fine needles in sagenite.

The hornblende is mainly in large xenomorphic plates inclosing the automorphic feldspars. This is the variety of hornblende known as uralite and is all presumed to be of a secondary nature. In no case does it possess the compact nature of original hornblende, but is always more or less fibrous, its fibrous nature being best seen along the edges, and less clearly shown, though still observable, where the sections are thicker. It varies

[1] A letter to Neues Jahrbuch, Vol. II, 1887, p. 263. The greenstone-schist areas of the Menominee and Marquette regions of Michigan. Bull. U. S. Geol. Survey, No. 62, 1890, p. 99.

from scarcely colored needles to those which are strongly pleochroic. The pleochroism varies from yellowish for 𝔞 to yellowish or olive green for 𝔟, and in many cases to a dark bluish-green for 𝔠. In a few cases much of the hornblende has frequently a darker shade in the center than at the border, although of the same color.

A somewhat different variety of hornblende is observed occupying round to oval areas in the dolerites. This is in tangled aggregates of needles, with which some chlorite is associated. This hornblende is automorphic in prismatic zone, ragged at the ends. These aggregates seem to be very coarse pilitic pseudomorphs after olivine. The areas occupied by these aggregates are similar in appearance to the pseudoamygdules described by Pumpelly as occurring in the Keweenawan lavas.

The hornblende is largely altered to masses of chlorite and epidote, usually with the production of some calcite, and to this is due the present extremely chloritic and epidotic characters of many of the badly altered specimens.

The secondary minerals, chlorite and epidote-zoisite, possess their usual characters. The chlorite is present in very large quantity, and next to it the epidote-zoisite is most common. These two minerals make up a large proportion of the rock. In one case porphyritic scalenohedra of calcite were found in a medium-grained dolerite, the occurrence in every way being similar to that described in the volcanics of the same region.

None of the original minerals of these intrusive greenstones give evidence of having been severely mashed; consequently we may safely conclude that they have not participated in the orogenic movements in pre-Keweenawan time which have universally affected the older rocks of the Crystal Falls district.

RELATIONS TO ADJACENT ROCKS.

Relations to Lower Huronian Mansfield slates.—The relation of the dolerites to the Mansfield slate is quite clearly shown along the line of contact between them. This extends from sec. 7 S. to sec. 32, T. 43 N., R. 31 W., on the east side of the Michigamme River, near Mansfield. The presence of numerous large inclusions of the slate in the dolerite and the occurrence of contact rocks in the slate plainly show that the dolerites are younger than the slate. Another piece of evidence pointing to this same relation was found in sec. 28, T. 44 N., R. 32 W. Here was found an angular inclusion

of sedimentary rock in a dolerite. The rock now possesses the characters of a spilosite, and was evidently brought up from below by these intrusives. No slate is exposed near this point, but it is presumed to underlie this area, although below the exposed volcanics.

Relations to Lower Huronian Hemlock volcanics.—The dolerite ridges which occur in the area underlain by the Hemlock volcanics are surrounded on all sides by rocks of related petrographical character. The number of localities at which the relations between the two may be observed are very few, but their relations where seen are clear. For instance, in secs. 18 and 30, T. 44 N., R. 32 W., the coarse intrusives break through the volcanics. In sec. 27, T. 46 N., R. 33 W., a boss of the dolerite occurs in the midst of schistose volcanic tuffs. The volcanics surrounding the intrusives exhibit symptoms of more or less violent dynamometamorphic action, whereas the dolerites in no case show any evidence, microscopically or macroscopically, of having undergone the metamorphism from which the volcanics have suffered. The dolerites are thus clearly younger than the effusives of the district.

Relations to Upper Huronian.—Only a few isolated dolerite outcrops have been found in the area underlain by the Upper Huronian. The most conspicuous outcrops are the large dike in secs. 7, 8, and 9, T. 43 N., R. 32 W., and the knobs in Ts. 42 N. and 43 N., R. 31 W. These last are practically continuous with the great dike which penetrates the Lower Huronian along the Michigamme River immediately to the north. One isolated knob has also been found in the extreme northwestern part of the district in sec. 19, T. 47 N., R. 33 W. Although in none of these areas have the dolerites been found in contact with the Upper Huronian, as it has been shown by the stratigraphy that these areas are underlain by the Upper Huronian sediments, the statement seems warranted that the dolerites are intrusive through them.

Relations to other intrusives.—In one place a dolerite is intruded by a dolerite of later age, and it is highly probable that there are many more similar cases never observed. The dolerites are cut by small granite dikes at several places east of Mansfield.

CONTACT METAMORPHISM OF MANSFIELD SLATES BY THE DOLERITE.[1]

The contacts between the dolerites and the sedimentaries are very rarely observable. For the most part where the sedimentaries are altered

[1] A contribution to the study of contact metamorphism, by J. Morgan Clements: Am. Jour. Sci., 4th series, Vol. VII, 1899, pp. 81–91.

by contact action they are surrounded on all sides by the dolerites, being in fact inclusions, but without the immediate contacts exposed. Such inclusions are rather numerous on the east side of the Michigamme River, from sec. 29 N. to sec. 8, T. 43 N., R. 31 W., near the boundary line between the Mansfield slates and the dolerites.

The Mansfield slates are uniformly rather fine grained, and the contact products are also fine-grained rocks, which still show in some cases the fine banding of the original slates. They are very dense "hornstone"-like rocks, have a splintery and at times almost conchoidal fracture, and vary in color from light to very dark gray and greenish The weathered surfaces in almost all cases are covered by a thin white to light-yellowish crust. This weathering brings out very clearly the banded and spotted character of some of the rocks.

The mineralogical components are quartz, feldspar, biotite, chlorite, white mica, actinolite, rutile, epidote, sphene, and iron oxide. Quartz is in very minute grains. Much of the feldspar shows fine striations, but owing to the minute size of the grains their exact characters are not determinable with the microscope, although from the very high percentage of soda shown by analysis to be present in the rocks the conclusion is drawn that they are grains of albite.

Biotite is present in small quantity in some of the contact products. This production of secondary biotite has been noted as rare for "diabase" contacts.[1] Plates of chlorite and white mica and needles of actinolite, the latter of much larger size than the individuals of the other minerals mentioned, lie scattered through the fine-grained mass of feldspar and quartz. Usually they are gathered together in bunches and sheaf-like or radial aggregates, but they occur at places in isolated individuals. Scattered through the slates is unmistakable rutile in coarse crystals with pyramidal ends. In only one case are the crystals very fine, and in that case they approach closely the appearance of needles in the clay slates (Thonschiefernadeln). These needles are commonly aggregated into tangled and roughly radial growths. The needles show very pretty knee- and heart-shaped twins.

Various combinations of the minerals occur, and the structures which accompany the combinations likewise vary. As a result of these variations there are found the different types of contact products described as spilosites,

[1] Mikroskopische Physiographie, by H. Rosenbusch, Stuttgart, 1896, Vol. II, p. 244.

desmosites, and adinoles.[1] The general characters of the minerals being the same, I shall describe the structure which characterizes the rocks.

SPILOSITES.

The ordinary spilosites are distinctly mottled in hand specimens and show clearly to the naked eye in thin section the oval spots which characterize them. These oval areas are commonly 4 millimeters long, and in rare cases even longer. They are frequently connected, forming chains. The spots are appreciably darker than the mass in which they lie, and are composed of chlorite, quartz, feldspar, and rutile, with a small amount of muscovite, the chlorite being the chief mineral. The surrounding mass consists essentially of muscovite, quartz, and feldspar, with rutile crystals and flakes of hematite, and with a very slight amount of chlorite. The different proportions of chlorite and muscovite seem to cause the difference between the spots and the groundmass (fig. *A*, Pl. XXXVII). In some of the spilosites we find a few flakes of biotite and needles of actinolite; however, these are always very subordinate in quantity to the chlorite.

In the ordinary form described these spots consist essentially of bisilicates. Others also have been noted in which these spots are white and lie in the fine-grained dark mass composing the greater part of the slides. Thus far it seems only one instance of the occurrence of such a variety of the spilosites has been described. This is by Van Werveke, to whose description reference is made by Zirkel[2] and Rosenbusch.[3] These white spots are composed essentially of albite feldspar, with only a minor amount of chlorite and epidote. The feldspar grains are much larger than those which take part in the constitution of the mass surrounding the spots. This mass is made up of quartz and feldspar, chlorite, epidote, and some sphene, with sheaves of actinolite scattered through it, and in one section clumps of biotite were observed mixed with the chlorite, though in very subordinate quantity (figs. *A* and *B*, Pl. XXXVI).

[1] Über den spilosit and desmosit Zincken's, by Lossen: Zeitschr. Deutsch. Geol. Gesell., Vol. XXIV, 1872, p. 701.

Durch diabas veränderte Schiefer im Gebiet der Saar and Mosel, by Van Werveke: Leonard's Jahrb., Vol. II, 1884, p. 225.

An interesting contact rock, with note on contact metamorphism, by W. M. Hutchings: Geol. Mag., Vol. II, pp. 122, 163.

Numerous other references may be found in Chemische Geologie, by Roth, Bd. III, and in petrographical works of Zirkel and Rosenbusch.

[2] Zirkel, Pet., Vol. II, p. 719.

[3] Rosenbusch, Vol. II, 3d ed., p. 1177.

Differing slightly from the ordinary spilosite is one in which the spots are of microscopical size, and consist of ragged bunches of chlorite and aggregates of sphene and epidote, with some flakes of biotite, which lie in a quartz-feldspar mass. The photomicrograph, fig. *B* of Pl. XXXVII, illustrates the appearance of the rock. As these spots increase in number they approach each other and unite, forming streamers, which in their turn unite and form bands (photomicrograph, fig. *A*, Pl. XXXVIII,). The spilosites or spotted contact products thus pass over into the desmosites or banded contact products.

Analyses of spilosites.—Analyses of two of the spilosites (Nos. I and II) were made by Dr. H. N. Stokes in the laboratory of the United States Geological Survey, and are here appended. With them there is given an analysis (No. III) by E. Kayser of a spilosite from the Harz Mountains

Analyses of spilosites.

	I (32827).	II (32861).	III.
SiO_2	57.77	52.51	55.56
TiO_2	.92	1.70	
Al_2O_3	19.35	19.00	18.15
Cr_2O_3	None.	None.	
Fe_2O_3	1.29	3.31	5.08
FeO	3.37	7.19	7.04
MnO	Trace.	Trace.	.51
CaO	1.71	1.55	1.40
BaO	None.	Trace.	
SrO	Trace.	Trace.	
MgO	4.35	3.29	3.17
Na_2O	8.22	6.72	4.20
K_2O	.22	.70	2.25
Li_2O	None.	Trace.	
CO_2	None.	None.	.10
P_2O_5	.04	.15	
H_2O at 110°	.18	.34	2.79
H_2O at 110° +	2.34	3.26	
S and SO_3	None.	None.	
Cl	None.	None.	
F	None.	Trace.	
Total	99.76	99.72	100.25

DESMOSITES.

Under the desmosites are included contact products composed of the same mineral constituents as the spilosites, but which show a distinctly banded structure. As shown in the discussion of the spilosites, the two must be very closely related and grade into each other.

E. Kayser, from Roth's Chem. Geol., Vol. III, 1890, p. 143, No. IV.

ADINOLES.

Chlorite has been the chief dark mineral in the contact products thus far mentioned, with actinolite as an accessory. In the adinoles actinolite is the characteristic constituent. The mineral constituents in the adinoles are, as a rule, more uniformly distributed than is the case with the spilosites; however, the spots are composed essentially of actinolite. The actinolite is in sheaf-like growths. These actinolite sheaves lie in an exceedingly fine grained mass of quartz and albite, with some flakes of chlorite and grains of epidote. The groundmass is formed of such minute mineral constituents that no conclusive test could be obtained for the determination of the limpid grains, and their nature has been concluded from the analyses. The rock is rendered rather dark by minute black specks disseminated through it. In places these are collected in irregular or lenticular heaps. They seem to be carbonaceous matter.

Analyses of adinoles.—The following is an analysis (No. I) by Mr. George Steiger, of the United States Geological Survey, of one of the typical adinoles from this district. With this there are given for comparison two adinole analyses (Nos. II and III) by E. Kayser.[1]

Analyses of adinoles.

	I (32465).	II.	III.
SiO_2	74.16	75.25	72.63
TiO_2	.37		
Al_2O_3	11.85	11.80	15.81
Fe_2O_3	.82	Trace.	
FeO	1.66	1.76	.74
MnO	.06		
CaO	2.10	.32	1.02
BaO	None.		
MgO	2.10	1.57	1.21
K_2O	.15	.61	.75
Na_2O	6.57	7.54	8.33
H_2O at 100° —	.05	.81	.61
H_2O at 100° +	.52		
P_2O_5	.08		
CO_2	.09		
FeS_2		.49	
C	.18		
Total	100.76	100.15	101.10

[1] E. Kayser, Zirkel, Vol. II, p. 721, Analyses III and VI.

There is still a kind of contact rock in which actinolite is the chief dark mineral, and in which the actinolite, though in clumps, is mainly collected in bands. This corresponds to the desmosites in structure, though differing from them in mineralogical composition.

These chlorite and actinolite contact rocks may be expected to grade into each other, and such a gradation is shown in one specimen, in which actinolite and chlorite are present in about equal quantity. The actinolite occurs in crystals and sheaves, forming the spots, whereas the main mass of the slide surrounding the spots is formed of chlorite as the metasilicate associated with feldspar, quartz, and some epidote.

It would be of great interest to determine which of the contact products, the desmosites, the spilosites, or the adinoles, represent the greatest amount of metamorphism, as shown by the relations to the intruding mass. Unfortunately, the records of the specimens do not enable me to determine this, although for other contact zones in other regions it has already been determined that the adinoles are next to the contact, while the spilosites (and desmosites) are intermediate between them and the clay slates.

COMPARISON OF THE ANALYSES OF THE NORMAL MANSFIELD CLAY SLATES AND THE CONTACT PRODUCTS.

In a series of analyses designed to illustrate the chemical changes which accompany the increasing metamorphism of a rock, it is of great importance that the various phases, from the unmetamorphosed to the most metamorphosed form of the rock, be represented. Moreover, the order of succession from the unmetamorphosed to the most metamorphosed form of the rock should be definitely known. In the present case certain pha es of the metamorphosed rocks are represented, but it has been impossible, owing to poor exposures, to determine in this locality the order of succession. This has, however, been done so satisfactorily by Lossen and others, and the characters of each facies in the progression have been so well described, that I have no hesitation, after a microscopical study of the thin sections of the specimens analyzed, in presenting the series of analyses in the following table as illustrative of the changes which have taken place in a clay slate, in the contact zone of dolerite, in its passage to spilosite and adinole. The analyses are given in the order of approach to the dolerite as determined by the character of the rocks. No. 1 is the unmeta-

morphosed form of clay slate; Nos. 2 and 3 are the intermediate phase, and No. 4 is the most metamorphosed phase.

Comparison of analyses of clay slate, spilosites, and adinole.

	1.	2.	3.	4.
SiO_2	60.28	52.51	57.77	74.16
TiO_2	.69	1.70	.92	.37
Al_2O_3	22.61	19.00	19.35	11.85
Cr_2O_3	----------	None.	None.	----------
Fe_2O_3	2.53	3.31	1.29	.82
FeO	.45	7.19	3.37	1.66
MnO	Trace.	Trace.	Trace.	.06
CaO	.13	1.55	1.71	2.10
BaO	.04	Trace.	None.	None.
SrO	----------	Trace.	Trace.	----------
MgO	1.35	3.29	4.35	2.10
K_2O	5.73	.70	.22	.15
Na_2O	.54	6.72	8.22	6.57
Li_2O	----------	Trace.	None.	----------
H_2O at 100°—	.60	×.34	×.18	.05
H_2O at 100°+	3.62	+3.26	+2.34	.52
P_2O_5	.03	.15	.04	.08
CO_2	None.	None.	None.	.09
C	.97	----------	----------	.18
S and SO_3	----------	None.	None.	----------
Cl	----------	None.	None.	----------
F	----------	Trace.	None.	----------
Total	99.57	99.72	99.76	100.76

×H_2O at 110°.
+H_2O above 110°.
No. 1 = Clay slate (Sp. 32497). Sec. 17, T. 43 N., R. 31 W., 450 N., 1620 W.; George Steiger.
No. 2 = Spilosite (Sp. 32861). Sec. 7, T. 43 N., R. 31 W., 750 N., 1380 W.; H. N. Stokes.
No. 3 = Spilosite (Sp. 32827). Sec. 7, T. 43 N., R. 31 W., 250 N., 325 W.; H. N. Stokes.
No. 4 = Adinole (Sp. 32465). Sec. 8, T. 43 N., R. 31 W., 500 N., 475 W.; George Steiger.

In these analyses the usual increase of silica as the dolerite is approached is at once noticeable, and hand in hand with it goes the diminution in percentage of alumina and iron oxides. The content of water and carbonaceous matter also suffers a diminution. The most noteworthy difference between the clay slate and the contact rocks is shown in the relations of potassa and soda. This is well brought out in an examination of analyses Nos. 1 and 2. It will be seen that there is only about one-eighth as much potassa in the contact rocks as in the normal clay slate; while, on the con-

trary, about 12 times as much soda as there was in the slate has been added to the contact rock. This causes a reversal of the relations of the soda and potassa, so that, whereas in the clay slate there is present 10 times as much potassa as soda, we find in the contact rock taken as a sample very nearly 10 times as much soda as potassa. The very considerable change in chemical composition, especially in the amount of silica and soda, seems to lend great weight to the supposition that in such contacts an actual transfer of material (soda-silicate) takes place from the basic intrusive to the slate. This idea is upheld by Roth,[1] Zirkel,[2] and others. W. Maynard Hutchings[3] advocates this view, and has described some interesting products as a result of the contact of the Whin Sill which still further support it.

NO ENDOMORPHIC EFFECTS OF DOLERITE INTRUSION.

Although the exomorphic contact effects of the dolerite intrusion were so obvious, no evidence is found that the dolerite itself suffered any change consequent upon its intrusion.

METABASALT.

Basalt has been described at length under the volcanics, where it plays an exceedingly important rôle. Basalt as a dike has been found in only two places, and therefore very little remains to be added.

The two basalt dikes occur within a very short distance of each other, in secs. 15 and 16, T. 42 N., R. 31 W., and are found penetrating the crystalline schists of the Upper Huronian. Their relations to the other intrusive rocks of the same region are not known. They are probably of the same age as the dolerites, of which they should most likely be considered offshoots.

These dikes are a porphyritic basalt. The phenocrysts were of augite, olivine, and labradorite. They were in a very fine groundmass of feldspar, augite, and iron oxide. However, the former existence of the augite and olivine phenocrysts is determinable only by means of their outlines. They are in very small quantity and are entirely altered to pilite. The feldspar phenocrysts are in coarse, heavy crystals and are remarkably fresh. The groundmass is very fine grained, and ranges from an exceedingly fine micro-

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[1] Chem. Geol., by J. Roth, Berlin, 1890, Vol. III, p. 145.

[2] Lehrbuch der Petrographie, by F. Zirkel, Vol. II, 1894, p. 722.

[3] Notes on the composition of clay slates, etc., and on some points in their contact metamorphism, by W. Maynard Hutchings: Geol. Mag., Vol. I, Dec. 4, 1894, p. 75. Chem. Geol., Vol. III, p. 145. An interesting contact rock, with notes on contact metamorphism, by W. Maynard Hutchings: Geol. Mag., Vol. II, 1895, pp. 122–131, 163–169.

ophitic texture to the pilotaxitic texture. The feldspars in it are in small lath-shaped individuals, and, like the phenocrysts, are fresh. The augite of the groundmass is to a great extent altered to uralite, and the iron ores to sphene.

One of the dikes is about 5 feet wide. In the center it is a moderately fine-grained rock; on the edges it is a dense aphanitic basalt. Even in thin section the gradation from the rock with microophitic groundmass to the one with a dense pilotaxitic groundmass is well shown. A dike of larger size might readily have cooled sufficiently slowly to have crystallized at its center as a dolerite.

ULTRA-BASIC INTRUSIVES.

Under this head are the descriptions of the picrite-porphyries (porphyritic limburgites).

PICRITE-PORPHYRY (PORPHYRITIC LIMBURGITE).

GEOGRAPHICAL DISTRIBUTION AND EXPOSURES.

The picrite-porphyries occur in isolated outcrops of comparatively small size in secs. 9, 22, and 27, T. 44 N., R. 32 W., in the area supposed to be underlain by the Lower Huronian Hemlock volcanics. They are surrounded by outcrops of the altered poikilitic dolerites, but the exposures are not such as to allow their relations to be determined. Their occurrence points to an intrusive character. It is on account of their field occurrence alone that we feel justified in describing them here under the general heading for this chapter, "Intrusives," instead of under the volcanics with the basalts, their proper place from a strict petrographical standpoint.

PETROGRAPHICAL CHARACTERS.

The picrite-porphyries are medium-grained rocks, which vary in color from gray to dark green and almost black. In general they have a porphyritic character. This is, however, not so well marked in the gray as in the darker-colored rocks. The gray ones have a spotted appearance. The spots are gray in color, fibrous, very rarely larger than 3 or 4 millimeters in length, and lie in a finely fibrous, dark-green matrix. In the dark rocks the porphyritic crystals reach a length of 1 centimeter, and are bluish to black, with silky luster. They lie in a fine-grained, more or less fibrous, green groundmass. In one of the dark rocks the magnetite is very noticeable. The crystals project from the weathered surface and the rock is strongly polar-magnetic.

The rocks originally consisted largely of olivine, pyroxene, hornblende, biotite, magnetite, and ilmenite. They now contain also, in considerable quantity, a chloritic product which seems to have been derived from the alteration of an original vitreous base. All of the specimens are exceedingly altered. The original mineral constituents have to a great extent been determined from their form, which in some cases has been preserved by the products of alteration, and by certain structures in the pseudomorphs. The minerals now composing the rock are original hornblende, biotite, apatite, magnetite, and ilmenite, with secondary amphibole, serpentine, chlorite, calcite, sphene, and rutile.

The two kinds of rocks, the gray and the dark-colored ones, were evidently derived from rocks of essentially the same composition. They have undergone different processes of alteration, and upon this depends the difference in color. As the study of these picrites is chiefly one of the alteration products of the minerals which composed them, it seems best to describe separately the two rocks showing the different products of alteration.

GRAY TREMOLITIZED PICRITE-PORPHYRY.

In the gray rocks the spots which are macroscopically observed are found under the microscope to consist of an aggregate of minerals. Examination of these aggregates shows them to be entirely secondary. A careful study of these aggregates shows them to consist of amphibole, magnetite, ilmenite, and serpentine, the first being predominant. No trace of the original minerals remains. The aggregates are the same in all of the crystals, and the only clue to the original mineral is the form of the pseudomorphs and certain structures in the aggregates. By means of the form the phenocrysts are readily divisible into three kinds. The first kind has a long prismatic habit, with pyramidal faces meeting at rather an acute angle. The iron oxide is arranged along certain lines, giving the characteristic mesh structure of serpentinized olivine. The second kind is a short, thick prism, for the most part with rounded ends, in some cases the pyramidal faces meeting in a rather obtuse angle. The iron oxide in some of these cases marks an imperfect parting perpendicular to the long direction of the prism. These are supposed to be pseudomorphs after a pyroxene. The third kind consists of round and irregular grains or plates, some of which may be referred to pyroxene, others to olivine.

The amphibole is in small needles. It has a very faint greenish tinge. In cross section it shows marked prismatic development. The character of the needles is plus in the long direction. The maximum angle found between $\mathfrak{c}$: c is 18 degrees. The needles appear to be tremolite containing some iron, and thus approaching actinolite in composition. Usually the needles have no regular arrangement, but in some of the pseudomorphs with rectangular outlines there is a parallel arrangement of such a number of the needles parallel to the long axis of the pseudomorphs as to give to the pseudomorph a distinctly uniform polarization effect.

Isolated crystals of magnetite and brownish transparent plates of ilmenite are scattered among the actinolite needles. By far the greater part of the iron oxide is collected in aggregates of small crystals and irregular grains. The formation and arrangement of these aggregates has in some cases taken place along fracture and cleavage planes of the original minerals, and thus in the pseudomorphs we see the mesh structure of olivine and transverse parting of pyroxene clearly brought out. In other cases the iron oxide is in irregular masses collected at the center or outlining the periphery of the pseudomorphs or scattered in small masses through them.

Between the tremolite needles and the iron oxide is a small quantity of minute fibers. They have a greenish tinge and low double refraction. Their extinction is parallel to the long c axis, which is also the axis of least elasticity. They are believed to be serpentine fibers. No definite arrangement of these fibers could be discerned over the greater part of the pseudomorphs, but in one crystal, on the edge of the section, where it is especially thin, the arrangement of these needles perpendicular to the long direction of the iron aggregates outlining the meshes is unmistakable. Calcite is in considerable quantity in some of the pseudomorphs. It is highly probable that it owes its origin to the alteration of the original mineral, though some of the calcium went into the amphibole.

Besides the above-described pseudomorphs after olivine and pyroxene, a few large prismatic and irregularly bounded areas were found among the phenocrysts, which now consist chiefly of chlorite, with grains of calcite, titanite, magnetite, and minute plates of ilmenite scattered through them. It is clear that the chlorite is derived from a hornblende, as shown by the presence of ragged remnants of hornblende which possesses uniform orientation throughout each area. This hornblende shows weak pleochroism in

the light-yellow to greenish tones of actinolite, although its character is more that of the compact hornblende. In one case its secondary nature was shown by the presence of a small irregular area of brown hornblende lying in a mass of the green. The two have the same orientation. In this case the chlorite is apparently a tertiary product, the original mineral being the brown hornblende, from which was formed the light-green variety, which in its turn alters to the chlorite.

Between the various pseudomorphs are irregular plates of compact, dark-brown hornblende, plates of biotite, large crystals of magnetite, and rough branching aggregates of ilmenite. These, while molded on the phenocrysts, themselves lie in the chloritic mass already mentioned, which also often completely surrounds the phenocrysts, and which is probably an altered vitreous base.

The pieces of brown hornblende which remain unaltered show moderately strong pleochroism, reddish brown for $\mathfrak{c}$ and $\mathfrak{b}$ and light brownish yellow for $\mathfrak{a}$. $\mathfrak{c}=\mathfrak{b}>\mathfrak{a}$. This hornblende contains inclusions of iron oxide and has all the appearance of an original mineral. By alteration it passes through a compact greenish amphibole to a much lighter colored, reedy, actinolitic variety of amphibole. In the secondary amphibole occur certain golden-brown grains with high single and double refraction, which are supposed to be rutile formed from the hornblende, and also some brown transparent plates of ilmenite. The orientation of the secondary hornblende is the same as the original. No further alteration of this amphibole was observed, but it is believed that the prismatic crystals altered to chlorite, calcite, and magnetite, as described above, are the extreme cases of alteration of an automorphic form of a brown hornblende very similar to the part described.

The biotite between the phenocrysts is in ragged areas either surrounding iron oxide or associated with it or with the hornblende. It is very pleochroic, the absorption parallel to the basal cleavage being so strong as to render the section opaque. Perpendicular thereto the color is a dark chocolate brown. The mica does not show its usual bright polarization colors in sections cut parallel to crystallographic c. This may be due in some measure to the very strong absorption. In some cases the biotite is seen to have a strong blue to violet metallic luster in incident light. The biotite has partly altered to chlorite. The alteration proceeds along the basal

cleavage. As this alteration progresses there is a lightening of the color of the biotite, and, as a consequence of this the whole cause of the metallic luster and the partial cause of the color of the biotite is disclosed. In the lighter biotite one by careful examination can see innumerable small plates of a brown or smoky color. At first sight they remind one strongly of the inclusions so common in many hypersthenes. Closer examination only emphasizes this resemblance, and they are believed to be micaceous ilmenite plates. These inclusions were studied by means of an oil immersion objective giving a magnification of about 1,250, and were found to have mainly a roundish or hexagonal outline. In addition to these, some plates of long, irregular form were observed. These are all isotropic and non-pleochroic. These minute plates lie parallel to the biotite lamellæ. The consequence of this is that in sections parallel to c one sees, for the most part, only short black streaks—the edges of the plates—whereas in the basal sections of the biotite one can determine the irregular or rounded contours of the plates. The plates are too small to allow the metallic luster to be seen on an isolated one. En masse they produce a very decided blue metallic shimmer, as seen in some of the biotite fragments.

Numerous apatite crystals occur. They are usually clear white, but one crystal was seen showing a dichroism from faintest brownish for rays perpendicular to crystallographic c to light smoky brown for rays parallel thereto. This crystal contains a core of brown glass.

Some of the iron oxide is in roughly rectangular masses, and appears to be magnetite. This is associated with an iron oxide, which occurs in opaque, ragged masses formed of long, irregular, and knotty stringers. These at places are parallel to one another and at other places cut one another at various angles, and at still other places meet at a common center, forming an opaque mass of varying dimensions, but usually small. Now and then one of the large magnetite masses constitutes a center from which extend the knotty, irregular stringers. The general appearance of these ragged masses is that described by German petrographers as *zerhackt*.

When these stringers pierce the section at an oblique angle, the ends are translucent, with a brown color, becoming more opaque as the section gets thicker. Such masses have all the appearance of ilmenite, and are believed to be that mineral. Similar ilmenite stringers are included in the chlorite, which results from the alteration of the biotite

The chlorite in the paramorphs after biotite shows extremely low blue polarization color, and the characteristic pleochroism—yellowish, tinged with red, when the rays vibrate perpendicular to the cleavage, and green when parallel thereto. Apatite needles included in the biotite are unaltered in the secondary chlorite.

Some of the minute octahedral crystals in the amphibole pseudomorphs after olivine appear to be slightly pellucid, with a brown color. If so, they might be referred to picotite, but there is doubt of the correctness of the observation, in view of the high power used, the oil immersion lens, and the fact that the search was for picotite. Close search was also made for perovskite, but none could be found, unless the transparent crystals very doubtfully referred to picotite are really perovskite.

Forming the matrix in which the pseudomorphs after hornblende, olivine, and pyroxene of these rocks lie, and frequently surrounding isolated crystals, one sees an aggregate composed chiefly of a fine felt of chlorite fibers. This alteration product contains a few apparently original apatite needles, some secondary grains of magnetite, and crystals of amphibole which are colorless or else show but the faintest tinge of green, and are larger than the amphibole crystals in the pseudomorphs. It is a secondary amphibole very poor in iron, probably highly calcareous, and approaching tremolite in composition. This chlorite aggregate shows no indication whatever of crystal forms. It seems to be the product of a homogeneous mass, such as would result from the decomposition of a vitreous base. Such a base the aggregate is presumed to represent, although no trace whatever of the glass has been observed in the rock, nor in view of the altered condition of the rock could such a glass be reasonably expected to still remain.

DARK SERPENTINIZED PICRITE-PORPHYRY.

The second variety of the picrite-porphyries is very dark greenish-black, and represents the results of a slightly different process of alteration from that by which the gray forms just described were produced. These dark picrite-porphyries show a very much better developed porphyritic structure than do the gray ones. This is due to the fact that the olivines in these rocks were well developed and reached a length of a centimeter. The olivines are completely altered, serpentine, pilite, and magnetite, being the products which form the pseudomorphs. The characteristic mesh structure

of altered olivine is well brought out by the serpentine and iron ore. In the centers of the meshes there remain small masses of a felt of tremolite needles (pilite). This alteration of the olivine corresponds to that first described by Lewis,[1] and more recently by Professor Bonney and Miss Raisin,[2] from a rock—kimberlite—very similar to the picrite-porphyries here described. He writes as follows: "It frequently happens that while serpentinization begins at the outside of a crystal, fibrous tremolite begins growing within, finally forming a mass of asbestiform fibers surrounded by a zone of green serpentine."

The minerals which composed these black picrite-porphyries were the same as those constituting the gray ones. These minerals were olivine, pyroxene, hornblende, biotite, magnetite, and ilmenite. They were cemented by a glass matrix. The glass is completely altered. All of the minerals are represented by pseudomorphs. Remnants of the original hornblende and biotite alone are preserved.

The contours of the original pyroxene crystals are filled with pilite, serpentine, and magnetite. The serpentine is present in greater quantity in these pyroxene pseudomorphs than it was in the pyroxene pseudomorphs in the gray picrite-porphyries. The alteration of the hornblende results in the production of an aggregate of chlorite inclosing grains of calcite, some sphene, and iron oxide, similar to that in the gray picrite-porphyries. The biotite, magnetite, and ilmenite also show those characters which have been described for the same minerals in the first-described picrite-porphyries.

Between all of the foregoing minerals we find a fine felty chlorite mass containing grains and dendritic masses of iron ore and a few needles of tremolite. This corresponds to the material forming the cement for the minerals in the gray porphyries, and, like that, is believed to represent an original vitreous matrix.

In one of the dark picrite-porphyries the magnetite is present in large quantity and is very noticeable, crystals of it standing out upon the weathered surface. This rock did not affect the magnetic needle very powerfully, though it was expected that it would do so. However, another one of

[1] On a diamondiferous peridotite and the genesis of the diamond, by H. C. Lewis: Geol. Mag., 3d ser., Vol. IV, 1887, p. 22.

Papers and notes on the genesis and matrix of the diamond, by the late Henry Carvill Lewis, edited by Prof. T. G. Bonney, London, 1897, p. 14.

[2] Notes on the diamond-bearing rock of Kimberly, South Africa, Part II, by Prof. T. G. Bonney and Miss C. A. Raisin: Geol. Mag., 4th series, Vol. II, 1895, p. 496.

these porphyries, in which, by the way, the iron content is relatively low, is unique, in that it is very strongly polar magnetic, and in this, as well as its probable original mineralogical composition, may be compared with the polar magnetic wehrlite from the Frankenstein, Hesse-Darmstadt, Germany.[1] The German rock shows tremolite scattered through the serpentine resulting from the olivine. It is a coarse, evenly granular rock, differing in this respect from the Crystal Falls rocks which are porphyritic.

An analysis (No. 1) of the polar magnetic serpentinized picrite-porphyry, in which great abundance of olivine was originally present, is here given, and there is placed with it for comparison an analysis (No. 2) of a very similar rock described by Darton and Kemp,[2] from New York. Both analyses were made by Dr. H. N. Stokes, United States Geological Survey. In No. 1 Ba, Sr, Li, Cl, S, and SO^3 were not looked for.

Analyses of picrite-porphyry.

	1.	2.
SiO_2	37.36	36.80
TiO_2	.79	1.26
Al_2O_3	4.76	4.16
Cr_2O_3	.62	.20
Fe_2O_3	6.61	....
FeO	6.12	8.33
MnO	Trace.	.13
NiO	.04	.09
CaO	1.19	8.63
BaO	....	.12
SrO	....	Trace.
MgO	31.11	25.98
K_2O	Trace.	2.48
Na_2O		.17
P_2O_5	.06	.47
CO_2	None.	2.95
SO_3	....	.06
S	....	.95
H_2O at 110°	.65	.51
H_2O above 110°	10.37	6.93
		100.22
Less O=S	....	.47
Total	99.68	99.75

[1] Der magnetstein von Frankenstein an der Bergstrasse, by Andreae und König: Abhandl. der Senkenberg. naturf. Gesell., Frankfort a Main, 1888, pp. 59–79.

Cf. Above article, p. 66, footnote, for references to other occurrences of tremolite associated with serpentine.

[2] Newly discovered dike at Dewitt, near Syracuse, New York, by N. H. Darton and J. F. Kemp: Am. Jour. Sci., Vol. XLIX, 1895, p. 461.

CLASSIFICATION.

These rocks just described, from their mineralogical composition, if we admit the presence of a vitreous base, would belong with the picrite-porphyrites of Rosenbusch.[1] This designation does not seem, however, to be appropriate, as he states[2] that he uses the term "porphyrite" only for certain textural phases of rocks containing lime-soda feldspar. He has evidently extended that definition so as to be able to use it for these picrites, considering that the glass possesses the necessary ingredients for the formation of such lime-soda feldspar, provided the conditions under which it cooled had been favorable for the feldspar development.

The porphyritic texture of these Crystal Falls picrites and the presence of a vitreous base[3] show them to be closely related to rocks of effusive character. Those which they most closely resemble among the younger basaltic lavas are the porphyritic forms of the limburgites (magma basalts).

One of the best-known rocks with which this may be closely compared, as far as association is concerned, is the rock first described by H. Carville Lewis as a saxonite-porphyry,[4] later called kimberlite. This was described by him as volcanic, and as associated with dolerites and melaphyres. He described it as a basic lava.[5] Other occurrences of very closely related basic rocks having a vitreous base have been described from the United States by Diller, Williams, Merrill, Branner and Brackett, Kemp, and Darton and Kemp.[6]

[1] Microscopische Physiographie, by H. Rosenbusch: 3d ed., Stuttgart, Vol. II, 1896, p. 1191.

[2] Op. cit., p. 436.

[3] Should the vitreous base be considered as not having been present and the rocks be put among the peridotites, then they would correspond very closely to the wehrlite described on p. 254.

[4] Papers and notes, cit., p. 50.

[5] The genesis of the diamond, by H. C. Lewis: Science, Vol. VIII, 1886, p. 345.

On a diamondiferous peridotite and the genesis of the diamond, by H. C. Lewis: Geol. Mag., 3d series, Vol. IV, 1887, p. 22.

[6] Dikes of peridotite cutting the carboniferous rocks of Kentucky, by J. S. Diller: Science, 1885, p. 65; Notes on the peridotite of Elliot County, Kentucky, by J. S. Diller: Am. Jour. Sci., Vol. XXXII, 1886, p. 188; Bull. U. S. Geol. Survey, No. 38, 1887.

The serpentine (peridotite) occurring in the Onondaga salt group, at Syracuse, New York, by G. H. Williams: Am. Jour. Sci., Vol. XXXIV, 1887, p. 137; Proc. Geol. Soc. Am., Vol. I, 1889, p. 533; Perowskit in serpentin von Syracuse, New York, by G. H. Williams: Neues Jahrb. Vol. II, 1887, p. 263.

On a peridotite from Little Deer Isle, in Penobscot Bay, Maine, by G. P. Merrill: Proc. U. S. Nat. Mus., 1888, p. 191.

The peridotite of Pike County, Arkansas, by J. C. Branner and R. N Brackett: Am. Jour. Sci., Vol. XXXVIII, 1889, p. 50.

Peridotite dikes in the Portage sandstone of Ithaca, New York, by J. F. Kemp: Am. Jour. Sci., Vol. XLII, 1891, p. 410.

A newly-discovered dike at Dewitt, near Syracuse, New York, by N. H. Darton and J. F. Kemp: Am. Jour. Sci., Vol. XLIX, 1895, p. 456.

The rock described by F. L. Ransome as a fourchite should perhaps also be compared with these

Hatch[1] has also described a very similar pre-Tertiary rock from England as a limburgite. Kemp[2] emphasizes the resemblance of the Dewitt dike to limburgite, and states that it should be called limburgite.[3] If we attempt to extend the use of the term "limburgite" to include the pre-Tertiary vitreous basalts, we shall have to include under it the rocks heretofore designated as picrite and picrite-porphyrite. Rosenbusch has now put the picrites and picrite-porphyrites with the effusive rocks, and if of these two sets of terms there is one to be discarded, it should be the name "limburgite." It seems preferable under the rules of priority to retain the name "picrite." It would then seem very suitable to apply to these pre-Tertiary porphyritic limburgites Hussak's old term, "picrite-porphyry," using the term "porphyry" simply with a textural significance.[4]

SECTION II.—A STUDY OF A ROCK SERIES RANGING FROM ROCKS OF INTERMEDIATE ACIDITY THROUGH THOSE OF BASIC COMPOSITION TO ULTRA-BASIC KINDS.

Beginning near the town of Crystal Falls, in isolated knobs, and extending southeast toward the Michigamme River, where the exposures are larger and better connected, there is found a series of rocks whose characters are of such interest petrogenetically as to warrant a detail description of them.

These rocks are all intrusive in character, with few exceptions are medium to coarse grained, and, while the granitic texture is predominant, there are certain facies in which the texture is porphyritic and even parallel. They have been only slightly affected by dynamic action, and these cases are purely local. Analyses show them to vary in chemical composition from those of intermediate acidity to those of ultra-basic character.

The prevailing rocks are, on the one hand, diorites of intermediate acidity ranging to more acid rocks, tonalites, quartz-mica-diorites, and

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rocks, representing as it probably does the olivine-free form of the limburgite (augitite). Geology of Angel Island, by F. L. Ransome: Bull. Geol. Dept. Univ. of California, Vol. I, 1894, p. 200.

[1] The Lower Carboniferous volcanic rocks of East Lowthian (Carlton Hills), by F. Hatch: Trans. Royal Acad. Edinburgh, Vol. XXXVII, 1892, p. 115.

[2] Op. cit., p. 460.

[3] "Taking plutonic rocks as practically the granitoid, and volcanic as the porphyritic, the Dewitt rock is a basaltic dike of the same composition and texture as limburgite, and should be called limburgite, even if it is not a surface flow." (Loc. cit., p. 460.)

[4] I believe E. Hussak was the first to use this term for a somewhat similar rock. Pikrit-phorphyr von Steierdorf im Banat, by E. Hussak: Verhandl. K.-k. geol. Reichsanstalt, 1881, pp. 258–262.

granite (plagioclastic), and, on the other, hornblende gabbros, gabbros, norites, and, lastly, peridotites of varying mineralogical character. These rocks thus resemble in their variations those Scottish plutonic rocks so well described by Messrs. Dakyns and Teall.[1]

The rapid changes in mineralogical composition and texture in a single rock, and the changes from one kind to another through intermediate facies, show very clearly the intimate relationship of these rocks to one another, and warrant the assumption that they all belong to a geologic unit, a conclusion reached a number of years since by Williams for a somewhat similar series, the Cortlandt series, from New York.

Granite is present as a local facies of the diorite. However, it is very subordinate in quantity and not altogether typical, and as no analysis has been obtained, its position is still more or less doubtful.

In the following pages only those kinds of rocks of which analyses have been obtained will be included in the final discussion. Others will be described in detail or merely mentioned, as representing facies of the main types, according to their petrological interest. The rock types of which analyses have been made are as follows: Diorite, gabbro, norite, and peridotite.

DIORITE.

NOMENCLATURE.

Diorite, according to the generally accepted definition, is a granular rock consisting essentially of hornblende, which must be primary, and a soda-lime feldspar.[2] The term has been used in a different sense by many writers on the Lake Superior and other regions. It has been used to comprise rocks which contain hornblende and plagioclase as preponderating constituents, it is true, but in which the hornblende is secondary, therein differing from a true diorite. These so-called diorites have been regarded as derived from an original dolerite (diabase) by uralitization of the pyroxene. By some writers these rocks have been classed with the epidiorites, thus recognizing their secondary nature, but by this name, epidiorite, unfortunately implying a false relationship.

In this paper, following Brögger, I restrict the name to the granitic

[1] On the plutonic rocks of Garabal Hill and Meall Breac, by J. R. Dakyns, esq., M. A., and J. J. H. Teall, esq., M. A., F. R. S., F. G. S.: Quart. Jour. Geol. Soc., Vol. XLVIII, 1892, pp. 104-121.

[2] Lehrbuch der Petrographie, by F. Zirkel, Leipzig, Vol. II, 1894, p. 465.

rocks of intermediate acidity, in which the feldspar is plagioclase and the bisilicate constituent is mica or primary hornblende. The feldspar is a lime-soda plagioclase.[1]

DISTRIBUTION AND EXPOSURES.

The distribution of the diorite is limited to a few localities, all of which are in the area underlain by Upper Huronian sedimentaries. The most typical occurrences, and those showing greatest variations, form knobs beginning near Crystal Falls and continuing to the south and southeast. Especially large outcrops form the hills in secs. 19 and 20, T. 43 N., R. 31 W. The smaller occurrences are not indicated on the map. These diorite exposures are always good, so far as getting fairly fresh specimens are concerned, but their contacts with other rocks are almost invariably deeply covered with drift; hence their relations in many cases are doubtful.

PETROGRAPHICAL CHARACTERS.

The diorites are holocrystalline rocks of medium to coarse grain. In texture they show some variation from those which are granitic to those in which the texture is imperfectly ophitic. The color is, on the whole, moderately light gray or reddish, but at times when the dark minerals become more prominent in the basic facies, especially where we get basic schlieren, the rock is very dark gray or greenish brown.

The important mineral constituents are feldspar, quartz, biotite, and hornblende. The accessory minerals are epidote, apatite, zircon, sphene, and iron oxides. The secondary minerals, white and brown mica, chlorite, biotite, epidote-zoisite, calcite, and rutile are also present.

Feldspar.—Plagioclase feldspar, orthoclase, and microcline occur together. The plagioclase is found in individuals which are fairly automorphic. In the ophitic textured diorites, the plagioclase is the best developed of all the essential constituents. In the granular rocks the degree of automorphism is highest where orthoclase and quartz are present in the largest quantity, and diminishes as these diminish, when the plagioclase individuals begin to interfere with one another's development. For the most part the plagioclase

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[1] Die Eruptivgesteine des Kristianiagebietes. I. Die Gesteine der Grorudit-Tinguait-Serie, by W. C. Brögger, 1894, No. 4, p. 93. II. Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol, 1895, No. 7, p. 35. Videnskabsselskabets Skrifter, I Mathematisknaturv. Klasse.

gives rather thin sections, though they can hardly be correctly called lath-shaped. No other form of plagioclase, showing a uniformly better or poorer development, or any other difference in character indicating the presence of two kinds of lime-soda feldspar, was observed.

The plagioclase sections almost invariably show polysynthetic twinning according to the albite law, with twinning lamellæ which vary from very thin to moderately thick plates, the thinner being the more common form. Very common is the combination of the albite and Carlsbad twinning laws in one individual. Less commonly we find individuals twinned according to the pericline as well as the albite law, and sometimes a Carlsbad twin is made up of individuals twinned according to the albite and pericline laws.

In determining the character of the feldspar, the Lévy method was followed.[1] A great number of measurements made on the zone perpendicular to 010 gave equal extinction angles, varying chiefly around 15 degrees, but running as a maximum to 19 degrees. From this it appears that the plagioclase is andesine, probably a somewhat basic kind. That these andesines vary slightly in composition is shown by a very slight but noticeable zonal structure, the more basic character of the center of the individuals being most admirably brought out by the more advanced condition of alteration of the center as compared with the periphery.

The andesine is for the most part very much altered, to such an extent that in many sections the boundaries of the twinning lamellæ are so blurred that measurements are rendered impossible. Muscovite, which appears in minute rectangular sections showing good cleavage, is the chief secondary product from the feldspar, with epidote-zoisite next in importance. Calcite and biotite are present, but in comparatively small quantities. In some cases muscovite almost replaces the feldspar; in others epidote-zoisite does so. In such a case one sees in the center of the feldspar only a mass of secondary mineral. As the examination is carried from the center toward the outside, the original feldspar material is distinguished as a thin film between the secondary minerals. This increases in mass until we reach the outside narrow rim of practically unaltered feldspar.

Orthoclase.—This is present in large quantity in irregular plates which form a part of the mesostasis for the plagioclase and bisilicates. Less commonly we find it in micropegmatitic intergrowth with the quartz. It is

[1] Étude sur la détermination des feldspaths, by A. Michel Lévy, Paris, 1894.

invariably more or less decomposed, and shows innumerable minute dark specks scattered through it. The quantity of orthoclase varies in these dioritic rocks considerably; at times it almost equals or even exceeds the plagioclase, when the rocks approach the granites, and at times it sinks to a few large plates in each section, when the rocks are a normal diorite.

Microcline.—This mineral is not abundant. It is in individuals which frequently, though not in all cases, are automorphic with respect to the orthoclase and quartz. It is remarkably fresh.

Quartz.—Quartz, at times, is an essential constituent, and again it diminishes in amount until it is present only in a few grains, or even disappears altogether. Like the orthoclase, it is completely xenomorphic, and with the orthoclase constitutes the mesostasis. Undulatory extinction in the quartz gives indication of slight pressure.

Biotite.—The original biotite in the granular dioritic rocks is automorphic with respect to all minerals but the hornblende. In the ophitic forms it has a development about equal to that of the hornblende. It shows a dark rich chocolate-brown or greenish-brown color for $\mathfrak{b}$ and $\mathfrak{c}$, and a light yellowish-brown for $\mathfrak{a}$. The biotite includes small epidote crystals with pleochroic courts and some grains of sphene. Both of these are original. The biotite is almost invariably more or less altered, bleaching in some cases to a very light colored mica with exceedingly high polarization colors. This bleaching follows along the laminæ of the biotite and results in giving sections parallel to the vertical axis a banded appearance resembling parallel intergrowths of muscovite and biotite laminæ. More commonly it alters to chlorite, rutile (often present as sagenite), sphene, epidote-zoisite, and calcite. There is also a distinct banding of the biotite and the chlorite in places. In the alteration of the biotite we very commonly find lenses of calcite produced between the laminæ. In some cases the epidote-zoisite is clearly a product of the alteration of the biotite, for in many cases it is found in the rectangular shape of the biotite section, and in other instances in spaces between the feldspars in the ophitic rocks, which in fresher specimens are found to be occupied by the biotite. Moreover, in the epidote-zoisite are minute grains of sphene similar to those contained in the original biotite.

Where it is present as a secondary product, it occurs with the muscovite and is xenomorphic with respect to it. The green tone is absent from the secondary biotite.

Hornblende.—The hornblende in the diorites shows a most excellent development in the prism zone; very much less well developed are the terminating planes. The color varies from dirty green to a reddish-brown. The brown hornblende occupies the center of the crystals, while the green occupies the outside, the green agreeing perfectly, optically, with the brown. A zonal structure is indicated by the difference in the character of the hornblende, though the zones are not sharply delimited, but grade into one another. In a few cases the greenish hornblende grades into one which is almost colorless. The pleochroism is as follows: Brown hornblende: $\mathfrak{a}$, light yellow or light reddish-yellow; $\mathfrak{b}$, light reddish-brown; $\mathfrak{c}$, darker reddish-brown. Green hornblende: $\mathfrak{a}$, light yellow; $\mathfrak{b}$, bright green; $\mathfrak{c}$, dull or olive green. This green hornblende is clearly original and not to be considered as a secondary product after the brown hornblende. Both kinds are free from inclusions.

Accessory minerals.—The epidote is observed very frequently inclosed in the altered biotite, and is surrounded by pleochroic halos. In such cases it is considered a primary constituent. The accessory minerals, apatite, sphene, and zircon, show none other than their usual characters. Titaniferous magnetite is present in the diorites in very small quantity.

According to the relative proportion of the important minerals just described—plagioclase, orthoclase, quartz, hornblende, and biotite—composing the diorites, we get the following varieties: Mica-diorite, quartz-mica-diorite, quartz-diorite, and tonalite. These grade into one another, as stated above; and, as will be shown later, certain of them grade into granites. On account of these variations these dioritic rocks are especially interesting.

DESCRIPTION OF INTERESTING VARIATIONS.

SEC. 15, T. 42 N., R. 31 W.

A dike of rock 4 feet wide, occurring at 425 paces N., 1050 W., sec. 15, T. 42 N, R. 31 W., near Norway portage, shows the following mineralogical variation. A specimen taken from the center of the dike shows the rock to be there a typical fine-grained granitite with little or no plagioclase. (Photomicrograph, fig. *A*, Pl. XXXIX.) Along the sides the dike rock is a mica-diorite consisting of mica and plagioclase without any quartz. Measurements on zone perpendicular to 010 gave equal extinction angles

with a maximum of 15 degrees. Only one kind of plagioclase is distinguishable by its mode of development, and this is rich in CaO, as shown by its alteration products. The feldspar ranges at most from albite to andesine. No chemical analysis has been obtained of either the granitite or the mica-diorite phase, but the mineralogical composition is sufficiently marked to show conclusively that we have here a gradation from a granitic to a dioritic rock rich in CaO. The idea has been suggested by Johnston-Lavis[1] that in some cases the variation in chemical composition of intrusive rocks, especially where this variation is one between the center and the periphery of an intrusive mass, may be due to resorption by the intrusive of parts of the rock intruded. The sharp line of demarcation which exists between the dike and the intruded hornblende-gabbro in the occurrence described above seems to preclude the possibility of a fusion and mingling of the two rocks.

ACROSS RIVER FROM CRYSTAL FALLS.

Near Crystal Falls, just across the river from the town, are a number of small knobs of granite grading into quartz-mica-diorite. They are medium-grained rocks, reddish to gray in color. They take a very fine polish and are well adapted to ornamental stonework, as is shown by the columns made from them which are used in the court-house at Crystal Falls. When examined under the microscope, the rocks are found to consist of automorphic biotite and plagioclase, with xenomorphic orthoclase and quartz, these last forming the cement. Some of the slides show beautiful micropegmatitic intergrowths of quartz and feldspar. The amount of quartz, plagioclase, and orthoclase varies so that, depending upon the specimen examined, one would call the rocks forming the knobs granite or quartz-mica-diorite. Most commonly the rock is a plagioclase-bearing granite. No analysis has been obtained of the granite, but it is confidently believed that the chemical composition would sustain the microscopical diagnosis. Within the granite there are found lenticular schlieren of considerably darker color than the main mass, in which the plagioclase is the preponderant feldspathic constituent. The rock of these lenses is essentially a quartz-mica-diorite.

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[1] The basic eruptive rocks of Gran (Norway) and their interpretation; a criticism by H. J. Johnston-Lavis: Geol. Mag., 4th ser., Vol. I, 1894, p. 252.

The causes of variation in the composition of igneous rocks, by H. J. Johnston-Lavis: Natural Science, Vol. IV, 1894, pp. 134–140.

These knobs are cut by a number of small dikes from a fraction of an inch to 3 inches in width. In all of these dikes the rock shows the same characters. It is very light gray to pink in color, and aphanitic.

An examination under the microscope enables the separation of each dike into a very compact fine-grained saalband and a somewhat coarser-grained porphyritic central portion. In the central part of the dike phenocrysts of quartz, feldspar, and biotite lie in a very fine groundmass of quartz and feldspar. The texture of this groundmass is micrograniti. The saalband is composed of the micrograniti groundmass without the phenocrysts. The quartz phenocrysts show the usual characters. The feldspar phenocrysts are in most cases so completely replaced by a muscovite aggregate as to preclude any exact determination of their original character. In some cases indistinct remains of polysynthetic twinning are seen. Even when the main mass of the feldspar phenocrysts is entirely altered, there is a narrow zone of very fresh feldspar material surrounding it. Twinning in the center is also continuous through this zone. Moreover, this zone itself shows a very noticeable zonal structure by the change in extinction angle observed in passing from the inner to the outer portion. This less altered zone of feldspar contains numerous inclusions of quartz from the groundmass. The character of the feldspar phenocrysts could not be determined, but the presumption is that they are of the same character as the feldspar in the coarser main mass—that is, andesine—with a more acid feldspar, possibly oligoclase, surrounding them. The further presumption is then warranted that the feldspar of the groundmass agrees with this outer feldspar zone in character—that it is also oligoclase, or at least is more acid than the phenocrysts. Automorphic biotite plates are now represented by chlorite pseudomorphs, with here and there some secondary epidote.

The groundmass consists chiefly of quartz and feldspar, but contains disseminated through it many minute plates of white mica and a few crystals of zircon. The feldspar of the groundmass is too small to permit of its accurate determination. A plagioclase feldspar in sections indicating an approach to automorphism was observed. Its character as oligoclase (?), or at least a feldspar of a more acid character than that of the centers of the phenocrysts, is surmised for reasons given above. Microcline in sections showing characteristic twinning and in more or less rectangular outlines was observed in considerable quantity. An untwinned feldspar was

determined as orthoclase by the difference shown by its refractive index and that of the twinned plagioclase. Quartz was also recognized in this way in the groundmass. The quartz and orthoclase form the cement for the other constituents. The muscovite in the groundmass is presumably secondary, as is that in the phenocrysts. (Figs. *A* and *B*, Pl. XL.)

The rock is here inserted as showing an exceedingly fine grained porphyritic form of the quartz-mica-diorite. It may compare to this mica-diorite as does the tonalite-porphyrite of Becke[1] to the tonalite described by him, and one might call it a quartz-mica-diorite-porphyry.

No analysis of this rock has thus far been obtainable. Possibly its chemical composition may indicate it to be more closely allied to the true granites than is believed to be the case, judging from its mineralogical composition and its association with the rocks on the border line between granites and diorites.

SOUTHEAST OF CRYSTAL FALLS.

Southeast of Crystal Falls, in sec. 16, northwest of Lake Tobin, and extending southwest into sec. 28, T. 42 N., R. 32 W., is a range of hills upon which are numerous exposures of a uniformly medium-grained rock. The main mass of the knobs is of tonalite, which shows several facies. A miarolitic texture is very common in this massif. The cavities are now filled with calcite, quartz, and epidote-zoisite alone or together. This last mineral occurs in single large individuals or in tufts of individuals, which radiate from one side of the cavity. In one case a cavity incompletely filled by such a tuft has been completely filled by a later infiltration of quartz. The color of the rock varies from light pink to very dark greenish gray. The areas of the lighter-colored rocks may be seen extending in finger-like projections into the darker-colored phases. There are, however, no sharp lines between these varieties, but a gradual passage from the lighter to the darker rock. These different phases evidently belong to a single rock mass. Under the microscope, however, important variations in the textural and mineralogical character of the rock masses are seen. The main mass of the rock is granular tonalite. The essential constituents are plagioclase, orthoclase, quartz, hornblende, and mica. The most common association of minerals is hornblende and mica in automorphic crystals,

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[1] Petrographische studien am Tonalit der Rieserferner, by F. Becke: Tschermaks mineral. Mittheil., Vol. XIII, 1892, p. 435.

with plagioclase somewhat less well developed. Between these there is found the quartz, with some accessory orthoclase, and microcline as the last products of crystallization. In some cases these two minerals are present in micropegmatitic intergrowths. A textural variation, which the facies mentioned below also undergo, is from a granular to an imperfectly ophitic texture. In such cases the order of crystallization of the hornblende-mica and plagioclase is reversed, the plagioclase being most automorphic in the ophitic varieties.

The rock resembles the tonalite described by Becke from the Rieserferner.[1] It also closely resembles some slides of the typical Adamello tonalite with which I have been able to compare it. The chief difference between them is that the plagioclase and hornblende have a better crystallographic development in the Crystal Falls rocks than in the Adamello tonalite, and that the accessory allanite of the Adamello rock is wanting in the Crystal Falls tonalite, though the normal epidote may represent it. The hornblende also differs slightly from that of the Adamello rock in that it is not throughout reddish brown. The central portion of some of the crystals shows this color, but the outer portion is a dirty green, even grading into an almost white hornblende.

The tonalite grades, by diminution of biotite, with corresponding increase of hornblende, into a quartz-diorite, and by diminution or disappearance of the hornblende and increase of the biotite into a quartz-mica-diorite.

Hornblende never occurs alone in the rocks, whereas biotite may occur as the only bisilicate constituent. It is a very common thing to find in the diorites rounded basic segregations consisting chiefly of mica with hornblende subordinate and just a little accessory feldspar. When the orthoclase and quartz diminish, we get the mica-diorites. Orthoclase is always present in all of these dioritic rocks. In certain facies orthoclase and quartz are very abundant and the plagioclase is correspondingly diminished. Such rocks are clearly plagioclase-bearing granites, and represent gradations between the ordinary tonalite and granite, and point to close relationship of this occurrence with the occurrences nearer Crystal Falls already described, in which the granitic facies predominates and the dioritic facies is subordinate.

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[1] Petrographische studien am Tonalit der Rieserferner, by F. Becke: Tschermaks mineral. Mittheil., Vol. XIII, 1892, pp. 364–379.

Similar gradations have been noted by Becke in the tonalite from the Rieserferner.[1] The diorite massif of the Crystal Falls district seems to correspond very closely to the granodiorite masses of Becke, Turner, and Lindgren,[2] which on the one hand grade into the granitites and on the other into the diorites.

ANALYSIS OF DIORITE.

It has not been found possible thus far to obtain analyses of all these varieties. The more acid facies of the diorites seem in their mineralogical composition to show very clearly their gradations toward the tonalites and granites. This being the case, it was deemed of more importance to study the relations of the more basic dioritic facies in order to determine the relationship of these rocks to those of the more basic gabbro and peridotite families which are found in association with them. To this end an analysis of one of the mica-diorites was obtained.

This rock contains the dark constituents, biotite and hornblende, in large quantity, and of these the mica predominates. Plagioclase predominates among the white silicates, with orthoclase and quartz very subordinate. The mica is considerably altered, but on the whole the rock is fairly fresh. Fig. *B*, Pl. XXXIX, is a photomicrograph of the rock and shows its general characters. The following analysis was made by Dr. H. N. Stokes, in the laboratory of the United States Geological Survey:

Analysis of diorite.

	Per cent.		Per cent.
SiO_2	58.51	K_2O	4.08
TiO_2	.72	Na_2O	3.11
Al_2O_3	16.32	H_2O at 100°	.23
Fe_2O_3	2.11	H_2O above 100°	2.00
FeO	4.43	P_2O_5	.30
MnO	Trace.	Co_2	None.
CaO	3.92	Total	99.17
MgO	3.73		

[1] Petrographische studien am Tonalit der Rieserferner, by F. Becke: Tschermaks mineral. Mittheil., Vol. XIII, 1892, pp. 379–464.

[2] The granodiorite of California appears from Lindgren's description (Granitic rocks of California, by W. Lindgren: Am. Jour. Sci., 4th series, Vol. III, 1897, p. 308; where can be found references to mention and descriptions of granodiorite) to correspond very closely to tonalite, though Turner uses the name as synonymous with quartz-mica-diorite (Geology of the Sierra Nevada, by H. W. Turner: Seventeenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 636, 724).

The altered character of the rock is readily seen in the large content of water. It is, nevertheless, not so marked as to render the analysis useless for purposes of determination.

The character of the plagioclase feldspar is clearly indicated by the relatively high percentage of lime. This high content in lime and the large amount of alkalies present, 7.18 per cent, clearly show its relationship to the diorite family. The content in potash feldspar and the possible derivation of the rock from a granitic magma is shown by the high content in potash. Possibly a considerable amount of the potash, with the greater part of the magnesia, should be deducted for the biotite which is so abundant.

This rock is one which it is somewhat difficult to place definitely in the existing division of rock families. The large amount of lime and the relatively low percentage of alkalies prevent the placing of the rock with the syenites. On the whole it approaches close to the monzonite group according to the chemical composition of the group given by Brögger. But it differs from this in that the lime (3.92 per cent) is too low to bring the rock within his limits (4.52 to 10.12 per cent).[1] However, if we consider the total of the alkaline earths (7.65 per cent) in the rock under discussion, we find that it comes well within Brögger's range (6.05 to 17.52 per cent) for a total of magnesia and lime. Moreover, the alkali total (7.19 per cent) is about right to warrant its classification in the monzonite group as a representative of the type of biotite-monzonite.

On comparing the analysis with that of true normal diorites, we find that the relative proportions of the alkalies are abnormal. The lime content is also too low for rocks of this character, and the magnesia is too high.

The above considerations seem to make clear the relationship of the rock to the monzonites and diorites. However, it is so intimately associated with and so evidently but a facies of the tonalite which is the dominant type where this rock occurs, that it is considered to be more closely related to the lime-soda feldspar rocks, in which the orthoclase is but accessory, than to the monzonite family of orthoclase-plagioclase rocks. It is therefore considered to be a mica-diorite.

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[1] Op. cit., Part II, p. 51.

GABBRO AND NORITE.

PETROGRAPHICAL CHARACTERS.

The gabbros and norites are holocrystalline rocks of moderately fine to coarse grain. They show a considerable variation in texture. Some, the finest-grained forms, possess a very good parallel texture (Pl. XLII, figs. *A* and *B*); others are noticeably porphyritic. A few have poikilitic textures (Pl. XLI, figs. *A* and *B*); less common is an approach to the ophitic texture of the dolerites. Most common of all the rocks are the hypidiomorphic granular ones (Pl. XLIV, fig. *A*, and Pl. XLIII, fig. *A*).

The rocks vary from a light grayish-green color for some of the coarse-grained ones, through darker greenish colored rocks to those of a dark brownish or greenish-black color for the finest-grained forms.

The important original mineral constituents are feldspar, mica, hornblende, pyroxene, and olivine. Apatite, sphene, zircon, rutile, octahedrite (anatase), brookite (?), and iron oxide occur as accessory minerals. White and brown mica, chlorite, hornblende, talc, serpentine, sphene, rutile, and calcite occur as secondary minerals.

Feldspar.—Both plagioclase and orthoclase are present in the gabbros and norites. Plagioclase is by far the most important. It occurs normally in the coarse-grained kinds of rock as broad tabular individuals. In the finer-grained, especially the porphyritic and poikilitic facies, the feldspar sections assume a broad, lath-shaped character. The sections show the characteristic polysynthetic twinning. Twins, according to the albite, pericline, and Carlsbad laws, are present, usually the albite and Carlsbad or the albite and pericline being combined; in some cases all three occur together. Twinning lamellæ vary in breadth, but on the whole are moderately narrow. Measurements made on the zone normal to 010 give equal extinction angles against the twinning plane, which reach a maximum of 34 degrees. The feldspar is evidently labradorite. A zonal structure is noticeable, and is especially shown by the alteration being more advanced in the centers of the individuals. It is possible that the labradorite is accompanied by a small amount of more acid feldspar, andesine in zonal growth with it. The alteration of the feldspar results in the production of the same secondary products formed from the slightly more acid feldspar of the diorites,

mica (both muscovite and biotite), epidote-zoisite, and calcite. The plagioclase shows very beautifully the effects of dynamic action in local granulation of the peripheries of the individual. Such lines of granulated feldspar can be followed through the sections, probably indicating shearing planes. Inclusions are common. Some stout rutile crystals were observed in the feldspar. In some cases minute hair-like needles, which in a few instances were of a size sufficient to admit of their ready determination as rutile, were also found penetrating the plagioclase. Crystals of apatite and iron ores are also commonly included in it. There have also been found in a few cases minute hexagonal plates, which are translucent, with brown color, and are presumably micaceous ilmenite.

Mention of the presence of orthoclase in these rocks is made with considerable doubt. Here and there a few plates of untwinned feldspar, showing a character somewhat different from that of the plagioclase plates, were observed. As will be seen, the possibility of its presence is indicated by the potash shown in the analysis.

Biotite.—The biotite in the coarsely granular rock is in irregular plates. They are frequently included in and attached to the outside of the hornblende. Its period of crystallization thus overlaps that of the hornblende, though on the whole being contemporaneous with it. In the fine-grained rocks biotite is better developed than the hornblende, and is apparently for the most part older than it. In color it varies from a rich reddish brown for rays vibrating parallel to the cleavage to a light yellow for those perpendicular thereto. It includes crystals of zircon and apatite, which are surrounded by pleochroic halos.

Hornblende.—In most of the sections hornblende is the most striking component. It is present in the gabbros in three different varieties. The most prominent kind is a reddish-brown hornblende, which has a dirty green hornblende commonly associated with it and frequently intergrown with it zonally. This hornblende occurs without the green, but the green is invariably associated with the brown. The two are optically continuous in the intergrowths. It is possible, though not susceptible of proof, that the green is the result of the incipient alteration of the brown. The second kind is compact, strongly pleochroic, common green hornblende, and the third is a noncompact, reedy variety of light-green hornblende. The first

two kinds of hornblende are presumed to be primary. The third variety is secondary, but secondary after the original hornblende, thus not affecting the character of the rock.

The first variety, the reddish-brown hornblende, occurs in the gabbros in anhedra. A zonal structure is marked by brown hornblende occupying the centers of the crystals and by dull green hornblende, which agrees optically with the brown, occupying the outsides. The brown hornblende is somewhat lighter colored than basaltic hornblende. The pleochroism is strong in the following colors: Brown hornblende: $\mathfrak{a}$, light yellow or red, with tinge of green; $\mathfrak{b}$, red brown; $\mathfrak{c}$, same or darker red brown, exceptionally yellowish-brown; $\mathfrak{c} \geqq \mathfrak{b} > \mathfrak{a}$. Green hornblende: $\mathfrak{a}$, greenish-yellow; $\mathfrak{b}$, yellowish- or brownish-green; $\mathfrak{c}$, dull olive green, frequently with bluish tinge; $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$.

This hornblende, with respect to its rather exceptional pleochroism and its general characters, seems to agree very well with that described by van Horn from very similar rocks from Italy, and, like that, is probably a very basic hornblende.[1] Twinning parallel to 100, $\infty P \infty$, is very common. An imperfect parting parallel to the orthopinacoid 100, $\infty P \infty$, was also observed in some cases. It is also indicated by the platy inclusions which lie in this plane In some of the sections where the green hornblende is not intergrown with the brown the green kind shows very commonly a system of fine striations parallel to the positive orthodome 101, $P \infty$. In rare cases the brown hornblende is intergrown with almost colorless hornblende, one end of a crystal being brown, the other faintly yellowish. Irregular mottled intergrowths of the two were also found.

The normal brown-green hornblende is rendered poikilitic in some specimens by a few rounded grains of perfectly fresh pyroxene, and also by plagioclase crystals which it includes. This same kind of hornblende is frequently rendered very dark by the number of exceedingly small inclusions which it contains, and in this, and also in its reddish-brown color, resembles so strongly many hypersthenes as to be readily mistaken for them upon cursory examination. These inclusions are of several kinds, all distributed throughout the same individuals. It is impossible in studying them

[1] Petrographische Untersuchungen über die noritischen Gesteine der Umgegend von Ivrea in Oberitalien, by F. R. van Horn: Tschermaks mineral Mittheil., Vol. XVII, 1897, Part V, p. 409.

to get any optical tests, except that of extinction, owing to the minute size of the inclusions and to the fact that where large enough for examination the tests were vitiated by the presence of the hornblende.

Of these inclusions some are readily distinguishable as rutile. Some of the larger of the crystals reach a length of 0.045 mm. and a thickness of 0.0125 mm. Numbers of them show the characteristic heart-shaped and geniculated twins of rutile, so that there is no doubt as to the determination. Associated with the rutile are other crystals 0.019 mm. long, which show the typical pointed pyramidal development of octahedrite (anatase). Still others show a flat tabular development somewhat similar to that of brookite, though these could not be positively determined as that mineral. The hexagonal plates of clove-brown color so frequent in hornblende and also in hypersthene occur also in this hornblende. They are believed to be micaceous ilmenite. The thin plates are translucent, thicker ones are less so, and those which are still thicker are opaque and metallic. The thin plates appear when on edge as fine, hairlike streaks. The thick ones appear in the same position as more or less rectangular bars or rods. Often these small plates are associated with masses of iron oxide, also included in the hornblende. This iron ore occurs in the plates and bars characteristic for ilmenite. These ilmenite masses are translucent only on the edges, where the slide has cut the mass in such a manner as to give an exceedingly thin section of the ore. At such places the ore is translucent with the same brown color as the thin plates. Another rare variety of the inclusions occurs in round grains of rich green color, and may possibly be a spinel.

In those sections in which both original brown and original green hornblende occur the inclusions are confined to the brown kind. Where the brown kind is surrounded by the green hornblende the inclusions gradually diminish in quantity as we approach the green zone. With this goes also, hand in hand, a lightening of the color of the including mineral (brown hornblende), and there is thus an imperceptible change from the brown to the green hornblende. Where the green hornblende occurs alone it is frequently as full of inclusions as is the brown hornblende of other sections. Individuals of the same sections differ from one another with respect to the quantity of the inclusions, some being crowded with them, while others are practically free from them.

This brown hornblende, on alteration, breaks up into aggregates of epidote-zoisite and light-green chlorite.

The second kind of hornblende is the perfectly fresh, compact, common dark-green kind, with pleochroism varying from yellow for $\mathfrak{a}$, to yellowish-green for $\mathfrak{b}$, and to bluish-green for $\mathfrak{c}$; $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$. This is found in very few cases. It appears in every instance to be a primary constituent.

The third kind of hornblende may be primary, although the evidence obtainable points to its secondary nature. It has a light-green color, and when examined for pleochroism exhibits a scarcely noticeable change. This hornblende differs very much from the other two hornblendes described, in that it is not compact, but occurs in aggregates of coarse reed-like (schilfaehnliche) individuals. Such aggregates do not at all resemble uralite. The individuals are far too coarse and wedge out at short distances within the aggregates. The aggregates occupy irregularly shaped areas. The aggregates consequently have a coarse patchy polarization. They are frequently surrounded by ragged pieces of biotite, just as are the plates of compact hornblende. Moreover, they occur in rocks which show pressure effects, and are best developed in those in which such effects are most marked. The aggregates rather frequently occur with irregular pieces of the greenish or brown compact interposition-bearing hornblende bordering the aggregates or in the midst of them. The light-green reedy hornblende never contains such interpositions, but does have associated with it fairly large grains of rutile, which may perhaps be considered as having been derived from the various titanium-bearing microlites in the original brown hornblende. The general appearance of these aggregates and their association with the original hornblende seem to point toward their secondary origin from the latter through the effects of pressure.

Pyroxene.—The pyroxene comprises both a monoclinic and an orthorhombic kind. These are the first of the bisilicates to crystallize in these gabbros. The monoclinic kind is of two varieties. The first is in colorless to faint-pink grains included in large plates of original brown hornblende. These grains have a well-developed prismatic cleavage. One basal section shows very nicely the characteristic pyroxene cleavage. The extinction measured against the prismatic cleavage reached as high as 50 degrees. This pyroxene is presumed to be augite. It never shows diallagic parting. In other sections the monoclinic pyroxene is a clear white to faintest

green malacolite or diopside. This is in roundish grains included in the original green hornblende, which it equals in quantity.

The orthorhombic pyroxene occurs in individuals which show fairly good prismatic development, but with rounded terminal faces. The prismatic cleavage is very well developed. A transverse parting is also common. The pyroxene is usually colorless, but in some cases a scarcely noticeable pleochroism was observed, varying from a faint-greenish tinge for rays vibrating parallel to $\mathfrak{c}$, to a yellow for those parallel to $\mathfrak{a}$ and $\mathfrak{b}$. It contains small, dark, streak-like intrusions, some of which under exceptionally favorable conditions are transparent, with a faint-greenish tinge The exit of the bisectrix in basal sections, as well as the parallel extinction, renders it easily distinguishable from the monoclinic pyroxene. The optical angle could not be measured, but was clearly very large, as the hyperbolas passed completely out of the field of view. The orthorhombic pyroxene is evidently enstatite or bronzite, and the pleochroism clearly points to its position near bronzite. A few crystals of rutile and also some of the ilmenite plates, so common in hypersthene, were found occurring in the bronzite. The ilmenite plates are in rather rare irregular patches in the crystals.

In many cases along the cleavage lines or around the edges of the crystals or along the transverse parting planes are narrow zones of a secondary yellowish-green, finely fibrous, serpentinous mineral. Beyond these zones is a pure white aggregate of secondary talc scales (Fig. *B*, Pl. XXXVIII). Among these scales are a few minute rutile crystals, and also a few black ferruginous specks, these products being probably derived from the inclusions in the bronzite, and the ferruginous material possibly to some extent from the mineral itself. In some cases, instead of the intermediate serpentine zone, the rather rare occurrence is observed of the passage of the bronzite directly into the talc aggregate.

Olivine.—The determination of the original presence of olivine in the gabbroic rocks is based upon very slight evidence. In some of the sections containing augite almost every individual of this augite has near its center a rounded, very rarely irregular area of yellowish-green fibrous serpentine. These areas are sharply delimited from the surrounding pyroxene, and the conclusion seems warranted that it resulted from the alteration of some mineral included in the pyroxene. The only bisilicate found in the rocks

of the district which crystallized before the pyroxene is olivine. In the peridotite, to be described in the next section, this is usually surrounded by monoclinic or orthorhombic pyroxene. This altered mineral is not important in quantity.

Iron oxide.—Ilmenite and titaniferous magnetite occur in some of the rocks in considerable quantity. Both alter to sphene and rutile.

Apatite.—Among the accessory minerals apatite is perhaps the most common, and, as usual, one of the very earliest minerals to crystallize. It is contained in all the essential constituents, and in biotite is surrounded by pleochroic halos. In some cases it has even crystallized before sphene. It is noticeable in some sections that great numbers of apatite crystals are arranged along lines representing sections of planes between the plagioclase plates, thus practically outlining the feldspar individuals.

Sphene.—In many cases in these gabbros sphene is found contained in some of the freshest rocks as an original accessory constituent. It is present in largest quantity in the very finest-grained gabbros, which show a parallel texture. In these rocks sphene in some cases surrounds an iron ore, which, to judge from the rod-like sections which are so common, is ilmenite. One might be led to think that the sphene was secondary in such cases, but the iron ore is perfectly fresh, and, considering that in the same thin section crystals of apatite are also surrounded by sphene, it seems clear that we may consider such sphene as original. It thus appears that a portion of the titanium oxide combined with the iron oxide first, forming the titanic iron ore. This was followed by the crystallization of the calcium-titanium compound, thus giving the sphene. In these rocks sphene is not in crystals, but in grains. These grains are arranged in long chains lying between the other mineral constituents and with the long direction of the individual grains, as well as of the lines of grains, parallel to the long directions of the other constituents of the rock.

Zircon and rutile.—Zircon is in very small quantity. Rutile shows its usual characters. It is most commonly associated with the octahedrite (anatase) and brookite (?) as inclusion in the hornblende. The iron oxide is chiefly present as ilmenite, with some titanic magnetite.

The secondary minerals have already been mentioned and their characters described under the description of the minerals from which they are derived.

DESCRIPTION OF INTERESTING KINDS OF GABBRO.

The minerals described above as the leading essential constituents of the rocks to be described may be combined in varying quantities. According to these combinations a number of different mineralogical types of rock may be produced. The wide range in mineral composition of the gabbroic rocks is equaled, if not surpassed, by similar variations noted by Fairbanks in certain rocks from Point Morrito, California.[1] It may cause the further description to be more readily understood if we preface it by the statement that all of these types, however, are simple facies of a single magma. The important phases which will be described are, in the order of their importance, hornblende-gabbro, consisting essentially of hornblende and labradorite; gabbro, consisting of monoclinic pyroxene and labradorite, and bronzite-norite, consisting essentially of bronzite and labradorite. The various mineralogical types exhibit very interesting ranges in texture in certain cases, to which attention will be called.

HORNBLENDE-GABBRO IN SEC. 15, T. 42 N., R. 31 W.

A hornblende-gabbro forms a large knob in sec. 15, T. 42 N., R. 31 W., just at the foot of the Norway Rapids, on the west bank of the Michigamme River. This exposure shows very prettily a change in texture. The change in texture is also accompanied by a slight mineralogical change. The knob is composed partly of a fine-grained granular, but more largely of a coarse-grained porphyritic, gabbro. The fine-grained portion is a pure gabbro composed of plagioclase and brown hornblende, with very little brown mica. No quartz was observed, nor was any orthoclase definitely determined. The plagioclase is in fairly well-developed automorphic plates. The hornblende is the brown variety, with numerous minute inclusions, which has already been described, and is not always so well developed as is the plagioclase. In places it plays rather more the rôle of a cement. This relation of the two minerals results in forming an imperfect ophitic texture in places, though on the whole the two minerals are about equally developed, and produce a granular structure. (Fig. *A*, Pl. XLIV.)

[1] The geology of Point Sal, by H. W. Fairbanks: Bull. Dept. Geol., Univ. California, Vol. II, 1896, p. 56 et seq.

The coarse-grained porphyritic gabbro forming the greater part of the knob consists of plagioclase, hornblende, biotite, and iron oxide, with a very small amount of pyroxene. The hornblende occurs in phenocrysts which have irregular rounded shapes instead of being well crystallized. Some of the largest phenocrysts have a diameter of slightly less than 1 centimeter. They are poikilitic, rendered so by inclusions of lath-shaped plagioclase and rounded grains of pyroxene. (Photomicrograph, fig. *A*, Pl. XLI.) This porphyritic hornblende is a dark reddish-brown variety containing such great numbers of minute inclusions as to be opaque in many places, which grades over into, and is in many places in optical continuity with, a dirty green hornblende. This green hornblende is in anhedra and forms the cement for the feldspar, and the two together the groundmass for the brown hornblende phenocrysts. The plagioclase is most commonly in broad, well-developed crystals, which frequently give quadratic sections. Some few grains of a pink monoclinic pyroxene are included by the hornblende.

SECS. 15, 22, 28, AND 29, T. 42 N., R. 31 W.

Exposures of a hornblende-gabbro with interesting facies associated with it occur in the southeastern corner of sec. 15, at the southeastern corner of sec. 22, extending east and west through the northern part of sec. 28, at the southeastern corner of sec. 28, and on the west bank of the Michigamme River in sec. 29, T. 42 N., R. 31 W., at the location N. 100, W. 1,250 paces. This is medium to coarse grained and of a gray color from a short distance. Examined at moderately close quarters, one distinguishes very readily a milky white feldspar and a black or dark-green hornblende in about equal quantities. The microscopical examination adds to these two minerals in a very subordinate quantity biotite, pyroxene, and orthoclase. The labradorite plagioclase is in medium-broad, irregular plates, though at times approaching a very distinctly lath-shaped form. The orthoclase is present in a few rare individuals in the form of irregular plates. The hornblende constituent is in irregular plates and varies in character. It may be the brown or the green variety already described, or the two together in separate individuals, or even the brown grading into the green. This green is original and not the alteration product of the brown. Biotite is the normal reddish-brown kind in irregular plates. The pyroxene is usually absent

from the sections of these rocks, but when present it is very rare, and occurs in small irregular grains not uncommonly intergrown with the hornblende and evidently older than the hornblende. It is light green in color, with a scarcely noticeable pleochroism. Its monoclinic character was readily determinable; but a more exact determination was not made. It does not, however, show diallagic parting, and is diagnosed as possibly diopside.

The feldspar shows the best development of the accessory minerals. It can rarely, however, be said to be automorphic. The texture is, on the whole, granular.

From a mineralogical study of the rocks alone, one would unhesitatingly place them with the diorites, especially if those facies were seen in which the pyroxenic constituent was wanting.

The following analysis (Sp. 23354), obtained from Mr. George Steiger, of the United States Geological Survey, shows the chemical composition of one of these rocks:

Analysis of hornblende-gabbro.

	Per cent.		Per cent.
SiO_2	49.80	K_2O	.61
TiO_2	.79	Na_2O	2.22
Al_2O_3	19.96	H_2O 100°—	.13
Fe_2O_3	6.32	H_2O 100°+	1.71
FeO	.49	P_2O_5	.07
MnO	....	CO_2	.15
CaO	11.33	Total	100.63
MgO	7.05		

An examination of the analysis shows that the microscopical determination of the rock as a diorite would be incorrect if we accept, as has been done in the preceding pages, Brögger's characterization of the diorite and gabbro families.[1]

The rock analyzed is hornblende-gabbro, as shown by the relatively high content in the characteristic alkaline earths, especially magnesia, which usually appears in inverse proportion to the silica, and in the low percentage of alkalies.

[1] Op. cit., Part II, pp. 35, 39.

HORNBLENDE-GABBRO DIKES.

One of the exposures of the above-described hornblende-gabbro—the one on the west bank of the Michigamme River in section 29—is very interesting on account of at least two different series of dikes which cut it. The coarse-grained hornblende-gabbro forms the main mass of the knob. The dike rocks may be divided into the fine-grained hornblende-gabbro forming the earliest dikes and the coarse-grained bronzite-norite forming the latest dike.

Some of the specimens of the fine-grained rock are massive, but the greater portion possess a distinctly parallel texture. These are distinctly micaceous. The rock of the dikes has in general very much the macroscopical appearance of a biotite-mica-schist. The dikes are very narrow, never more than 18 inches wide. The larger ones send off branches, and in places inclose angular pieces of the coarse diorite. Thus the relation of this fine-grained rock to the main gabbro mass is perfectly clear, though in places it so closely resembles, macroscopically, pieces of mica-schist that in spite of the branching of these dikes, indicating their intrusive nature, they were supposed by one observer to be curiously shaped stringers of the mica-schists included in the main mass of the gabbro.

The notes do not indicate from just what portions of the dike the specimens were taken; hence it is impossible to state positively that the more schistose parts are nearest the edges and the more granular portions nearer the center, as one would naturally expect. However, in all but one of the specimens which show a contact between the dikes and gabbro which they penetrate, the rock nearest the contact shows a parallel structure. Hence it may be stated that in some cases the edges of the dikes are the more schistose portions. The one specimen referred to above is granular and much finer grained along the contact than farther from it.

The microscope shows the rock of these dikes to be a gabbro differing little in character from the main mass. The plagioclase is well developed in rectangular, more or less lath-shaped crystals. Mica of a rich brown color is rather more abundant than usual, and is in about equal quantity with the hornblende. The hornblende is brown or of a dirty greenish color, containing the inclusions mentioned in the detail descriptions of the minerals of the gabbros. Some irregular grains of a light-green augite (diopside) were observed in the sections. Orthoclase (?) in grains is present simply

as an accessory. Ilmenite occurs in irregular masses in rod-shaped pieces. Sphene is present in original grains and also as a secondary product after ilmenite. Apatite occurs and is sometimes included in the sphene.

The most striking feature of the rock is its textural variation. Some of the sections show very good granular texture; others have a fair ophitic texture; the most common is a striking parallel texture which macroscopically gives to the rock a schistose appearance. This may be seen even in the same section with the ophitic texture, the two grading into each other. The parallel texture is occasioned by the arrangement in a common direction of the long diameters of nearly all of the minerals (figs. *A* and *B*, Pl. XLII). The grains of sphene often lie in long trains agreeing with this general parallelism. One's first idea would probably be that the texture was due to the cause which has produced parallel structures in most other ancient rocks—pressure. However, it can not be referred to this, as the minerals—with some individual exceptions—show slight or no pressure effects. Apparently the only explanation borne out by the facts in this case is that we have to do with a fluidal texture, produced by the movement in the magma consequent upon its injection along the fissures in the gabbro, the parallelism of the minerals agreeing with the bounding sides of the fissure.

BRONZITE-NORITE DIKE.

The main hornblende-gabbro and the fine-grained dikes just described are cut by a dike, about 3 feet wide, of coarse rock which resembles that forming the main mass of the knobs in every way except that it contains a very much altered orthorhombic pyroxene (bronzite) in greater quantity than the hornblende. The rock is a very pure kind of bronzite-norite (fig. *B*, Pl. XLIV). The following analysis (No. 1, Sp. 23755), by Mr. George Steiger, shows the gabbro affinities of the rock. The high percentage of magnesia gives a clear indication of the important rôle played by the bronzite in the composition of the rock.

With the analysis of the bronzite-norite there is placed for comparison an analysis (No. 2) of a norite from Ivrea, Italy, which is essentially the same as the above in mineralogical as well as chemical composition. In the Italian rock hypersthene, instead of bronzite, is the chief pyroxenic constituent.[1]

[1] Petrographische Untersuchungen über die noritischen Gesteine der Umgegend von Ivrea in Oberitalien, by F. R. van Horn: Tschermaks mineral, Mittheil., Vol. XVII, 1897, Part V, p. 404.

Analyses of norites.

	1.	2.
SiO_2	48.23	49.95
TiO_2	1.00	.69
Al_2O_3	18.26	19.17
Fe_2O_3	1.26	4.72
FeO	6.10	6.71
MnO	....	Trace.
CaO	9.39	9.61
MgO	10.84	5.03
K_2O	.73	.74
Na_2O	1.34	3.13
H_2O 100° —	.26	.09
H_2O 100° +	2.00	
P_2O_5	.07	Trace.
CO_2	.43	....
Total	99.91	99.84

SEC. 29, T. 42 N., R. 31 W., 1,200 N., 200 W.

On the east bank of the Michigamme River at 1,200 paces N., 200 W., sec. 29, T. 42 N., R. 31 W., there is an outcrop which shows even better than the occurrence just described the variation in mineralogical character and the relative ages of these varieties. At this place there is a knob composed of hornblende-gabbro essentially like the general type described as typical for this district. This knob is cut by a rock which is coarser in grain and a trifle darker than the variety which it intrudes. Examined under the microscope, it is seen to differ from the normal phase also in mineralogical composition, and resembles rather closely in this respect the porphyritic variety described on p 240. Like that, the hornblende is reddish-brown, containing a large number of inclusions and grading over into the green hornblende. This hornblende includes rounded grains of a white to pinkish monoclinic pyroxene in sufficient quantity to be characteristic. The pyroxene is never automorphic, as one would perhaps expect to find it, though it was evidently one of the first minerals to crystallize. Contained in the pyroxene individuals are rounded areas of yellowish-green serpentine. These areas are sharply outlined from the pyroxene and do not appear to be the result of its alteration; consequently the conclusion is reached that the

serpentine results from the alteration of a mineral older than the pyroxene. Most probably this mineral was olivine, though no positive statement to that effect can be made. This pyroxene rock also contains an exceedingly large quantity of apatite. No analysis was obtained of this facies, but the microscopical characters enable us to place it as a gabbro (possibly olivine-bearing) and to consider it, like the bronzite-norite, as a facies of the predominant hornblende-gabbro.

This same exposure of gabbro is cut by a coarse peridotite (wehrlite), a description of which will be found on p. 253. In this peridotite there is found a narrow strip of rock, about 2 inches wide, which is presumed to be either an inclusion or a very narrow dike in the peridotite. The exposure does not admit of its relations being determined more accurately. The presumption is that it is a dike. Whether an inclusion or a dike, it is younger than the massive hornblende-gabbro forming the main exposure. In this respect it corresponds to the gabbro just described (p. 243) as cutting the normal gabbro.

This dike rock is macroscopically a fine-grained, granular, dark-gray rock. The microscope shows it to be very fresh, porphyritic in texture, and composed of phenocrysts of bronzite lying in a finely granular groundmass of plagioclase, hornblende, and orthorhombic and monoclinic pyroxene. No quartz whatever was found associated with these minerals. The plagioclase is the usual kind, labradorite. Some unstriated feldspar, possibly orthoclase, was also observed, though in very small quantity. The bronzite is in narrow prisms which reach a length of 1.23 mm. Commonly they have well-developed transverse partings. It is worthy of note that a few of the crystals contain the brownish platy inclusions so common in hypersthene. There is, however, no relation between the color and pleochroism of the mineral substance and these brownish plates. The bronzite is very clear, with weak color, showing a scarcely distinguishable greenish tinge for the rays vibrating parallel to $\mathfrak{c}$, with yellowish for the rays parallel to $\mathfrak{a}$ and $\mathfrak{b}$. In one case the bronzite was seen altering to a greenish-yellow fibrous aggregate of serpentine. In the groundmass this same orthorhombic pyroxene is represented by irregular grains. The hornblende is the usual reddish-brown kind, but differs from that seen in the other gabbros of this district in that it contains ilmenite inclusions only, without any rutile or anatase. It is in anhedra. A faint-greenish pyroxene occurs in irregular

xenomorphic individuals, forming a somewhat smaller proportion of the groundmass than does the hornblende, but is more abundant than the bronzite of the groundmass. Sphene is present in considerable quantity, and likewise ilmenite (fig. *A*, Pl. XLV).

This rock stands between the hornblende-gabbros and the norites. In texture it might be compared with the norite-porphyrite (enstatite-porphyrite of Rosenbusch) with holocrystalline groundmass. But it differs essentially from this rock in the presence of a large quantity of hornblende. This hornblende connects it with the hornblende-gabbros, from which its content of pyroxene, both orthorhombic and monoclinic, tends to separate it. Owing to its obvious relation to the bronzite-norites, which, like it, occur as differentiation facies of and dikes in the hornblende-gabbro, I shall call it a "bronzite-norite-porphyry," using the term "porphyry" purely in a textural sense.

The rocks may be compared, in their variation, to those described by G. H. Williams from Maryland,[1] by Chester from Delaware,[2] and by Fairbanks from California.[3] A series of basic rocks similar in many respects to those of Crystal Falls has also recently been described in two interesting papers by Van Horn[4] and Schaefer.[5]

DYNAMICALLY ALTERED GABBRO.

Near the junction of secs. 26, 27, 33, 34, T. 43 N., R. 31 W., there is a large gabbro mass which shows marked evidence of dynamic action, and may well be cited as an example of a metamorphosed gabbro, or, perhaps more clearly, as a rock intermediate between a hornblende-gabbro and a hornblende-gneiss. None of the gabbros thus far described show any evidence of having taken part in very extensive orogenic movements. The minerals of but few of them show more than the common phenomenon of slight wavy extinction. Hence it is clear that their intrusion took place

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[1] The gabbros and associated hornblende rocks occurring near Baltimore, by G. H. Williams: Bull. U. S. Geol. Survey No. 28, 1886; Outline of geology of Maryland, Baltimore, 1893, p. 39.

[2] The gabbros and associated rocks in Delaware, by F. D. Chester: Bull. U. S. Geol. Survey No. 59, 1890.

[3] The geology of Point Sal, by H. W. Fairbanks: Bull. Dep. Univ., California, Vol. XI, 1896, p. 56 et seq.

[4] Petrographische Untersuchungen über die noritischen Gesteine der Umgegend von Ivrea im Oberitalien, by F. R. van Horn: Tschermaks mineral., Mittheil., Vol. XVII, 1897, Part V, pp. 391–420.

[5] Der basische Gesteinzug von Ivrea im Gebiet des Mastallone-Thals, by R. W. Schaefer: Tschermaks mineral., Mittheil., Vol. XVII, 1898, Part VI, pp. 495–517.

after the occurrence of the mountain-building movements to which the intruded rocks have been subjected. It is not believed that the mass referred to in this description is an exception to the general rule, but that its metamorphosed condition is referable to local causes, such as have produced the shearing planes to which allusion has been made (p. 234). It may perhaps occur near or along some minor fault plane, though no indications of a fault have been observed.

The outcrop is composed in part of massive gabbro and in part of the metamorphosed kind. The gabbro in its typical massive form (fig. *A*, Pl. XLIII) is a medium to coarse grained granular rock, composed essentially of plagioclase and dirty brown-green compact hornblende, the latter being quite full of the inclusions mentioned above as commonly occurring in the hornblende of the rocks in this region. In the metamorphosed rock the grain is much finer, the rock possesses imperfect schistosity, and the color is a lighter green than in the original. The component minerals are chiefly hornblende and feldspar, with some quartz, chlorite, epidote, calcite, and rutile. The hornblende has a light-green color. It occurs mainly in aggregates of small irregular grains. In some cases these surround an angular nucleus of dirty brown-green original hornblende containing the same inclusions and in every way similar to that of the coarse-grained uncrushed rock. The light-green hornblende contains none of these minute inclusions, and only here and there grains of rutile, which, if the diagnosis of the interpositions as titanium minerals is correct, may possibly be considered as having been derived from them. This hornblende is believed to be secondary. It is produced by a process of mechanical breaking down of the original hornblende, accompanied by recrystallization. The process is somewhat similar to the crushing of ordinary plagioclase and the production of a more acidic variety. As may be seen from the photomicrograph (fig. *B*, Pl. XLIII) of a section, the feldspar exhibits signs of intense crushing. The twinning lamellæ are strongly bent, and the pieces possess wavy extinction. Many, in fact most, of the feldspars are fractured. Wherever these fractures occur the feldspar along the edges of the fractured portions has been altered, producing secondary epidote, muscovite, plagioclase feldspar, and quartz; the last, however, in small quantity. The biotite has been crushed. This has partly altered to chlorite, and the latter contains many grains of epidote. Some granular calcite and considerable iron

pyrites are also found in the altered rocks. These secondary products are easily distinguished from the original minerals by the total absence in them of wavy extinction. The effect of the crushing upon the texture has been to render it more or less schistose, the resulting rock resembling in its mineralogical character, and in texture, an ordinary hornblende-gneiss, or, when quartz is present in but small quantity, a plagioclase amphibolite.

RELATIVE AGES OF GABBROS.

An attempt to determine the relations of the varieties described resulted in the establishment of the following order of intrusion: The typical coarse-grained hornblende-gabbro was the first formed, and seems to be the most widely distributed. This was then intruded by dikes of gabbro, which contain both monoclinic pyroxene and hornblende in association and represent a gradation to the normal gabbro. These hornblende-gabbros and normal gabbros were then cut by the dikes of bronzite-norite and bronzite-norite-porphyry.

PERIDOTITES.

Until recently all of the ultrabasic rocks were included by most petrographers under the family name of peridotite. In the last edition of his Mikroskopische Physiographie, Rosenbusch has separated these rocks into the plutonic rocks and the volcanic rocks. The term "peridotite" is restricted to the first, and the last are called the "picrites." The characteristic differences between these two types are very clearly shown in the specimens from the Crystal Falls district which I have had the opportunity of studying. The rocks here described agree with Rosenbusch's narrower definition of the peridotites.[1]

DISTRIBUTION, EXPOSURES, AND RELATIONS.

The peridotite dikes were all found near the Michigamme River, in secs. 29 and 22, T. 42 N., R. 31 W. Typical wehrlite with very little green amphibole is found on the east bank of the Michigamme river, near the center of sec. 22, T. 42 N., R. 31 W. It shows no relations to the other rocks. The amphibole-peridotite, exhibiting marked variations to wehrlite and olivine-gabbro, forms an outcrop on the east bank of the Michigamme River in the NE. ¼, sec. 29, T. 42 N., R. 31 W. This dike cuts the gabbro.

[1] Op. cit., p. 343.

A rock to be described last, connecting the diorites, gabbros, and peridotites, was taken from near the northeast corner of sec. 22, T. 42, R. 31, where it is found cutting the gabbro.

PETROGRAPHICAL CHARACTERS.

The peridotites are very dark green to black coarse-grained rocks, showing in almost all cases a granular texture. In one case an excellent poikilitic texture was observed, and in another the same texture in a very imperfect condition was seen. The almost total absence of any pressure phenomena in these rocks excludes the idea of their having been subjected to any powerful dynamic action. The chief mineral constituents, arranged in order of relative amounts, are pyroxene (monoclinic and orthorhombic), olivine, hornblende, and biotite. The following minerals also occur associated with these: Feldspar, apatite, green and brown spinel, and iron oxide.

Pyroxene.—There is present in these rocks both orthorhombic and monoclinic pyroxene. The orthorhombic has a yellowish tinge, and contains a few tabular inclusions. Only a few grains of this pyroxene were found, but upon one section a figure was obtained and the positive character of the mineral was determined. It appears to be bronzite. The bronzite grains are found included in the hornblende. Its relations to other minerals are not shown in any of the thin sections.

The monoclinic pyroxene, though one of the earliest minerals to crystallize, is likewise in xenomorphic individuals, many of them twinned, some polysynthetically. It is usually of a light yellowish color, and is then nonpleochroic; in some sections, however, it is sufficiently colored to show pleochroism from light yellowish to brownish. It includes a number of the clove-brown tabular interpositions like those in the hornblende, and these at times give the pieces a decided violet tinge. Less commonly than the tabular interpositions one observes green needles and laths, more rarely rounded grains or plates of larger size and having a brownish-green color. They are so minute as to defy positive determination, but are presumed to be hornblende microlites. The orthopinacoidal parting is in some cases well developed in the augite. This diallagic augite is in large quantity, and though usually included in the hornblende, nevertheless includes both hornblende and biotite in a few ragged plates. Such sections are probably those which have passed through the outer edges of the augite crystals.

Olivine.—This is present most commonly in round anhedra, and is usually almost entirely altered to yellowish-green serpentine fibers. When the olivine is completely altered, the mesh structure affords a ready means of recognizing the original mineral, especially when taken in conjunction with grains of a rich-green isotropic mineral, and also octahedra and grains brown in color, probably spinels, which are found included in the pseudomorphs.

Hornblende.—The most of the hornblende in the peridotites is a brown variety showing strong pleochroism. $\mathfrak{a}$ is light cream-yellow, $\mathfrak{c}$ is yellowish brown, and $\mathfrak{b}$ is reddish brown; $\mathfrak{b}>\mathfrak{c}>\mathfrak{a}$. Patton[1] has already called attention to the pleochroism of the hornblende, which "is exceptional, inasmuch as the brownest color is that of rays of light vibrating parallel to the orthodiagonal axis." The brown hornblende is accompanied by a very small quantity of green hornblende. Moreover, the brown hornblende grades over into a light green, the two being in perfect crystalline continuity. In rare cases this brown hornblende is also intergrown with a light-green pyroxene in such way as to give a mottled polarization effect. The pinacoidal cleavage of the hornblende continues through the pyroxene, and the extinction angle of the hornblende against this cleavage is 19 degrees, while that of the pyroxene runs up to 34 degrees. The hornblende includes numerous anhedra of pyroxene, somewhat fewer grains of olivine, and, less commonly, ragged pieces of biotite, giving it a poikilitic character. It is also very full of opaque metallic or brownish translucent plates of ilmenite. In some individuals minute clear microlites, similar to those described above in the hornblende of certain gabbros, are noticed in small quantity. These are irregularly distributed in the hornblende, giving the crystals a patchy appearance. In respect to its color and these inclusions, this hornblende, as noted by Patton, bears a rather striking resemblance to hypersthene on superficial examination.[2] Iron ore in large masses is fairly frequent as an inclusion, and it is very commonly noticeable that where such inclusions occur the zone of hornblende immediately surrounding them is free from the platy inclusions mentioned above. Such a clear zone is also observed at times surrounding the inclusions of biotite and olivine, but never in case of pyroxene. Where these clear zones surround the

[1] Microscopic study of some Michigan rocks, by H. V. Patton: Rept. State Board of Geol. Surv. for 1891-92, 1893, p. 186.

[2] Loc. cit., p. 186.

included biotite or olivine, these two minerals have associated with them numerous small grains of ore, which probably represent the iron that would have been incorporated in the surrounding hornblende but for some selective influence exerted by the olivine and biotite.

Biotite.—This mineral is present in flakes of very irregular outline. The pleochroism varies from cream color to yellowish red or brown. Although one of the last minerals to crystallize, its crystallization began before that of the pyroxene or hornblende had entirely finished. Hence we find flakes of it included in these minerals, but near the edges of the crystals. The biotite itself is almost free from inclusions, containing only a little hematite and magnetite. It alters to a brilliant green, strongly pleochroic, chloritic mineral.

Feldspar.—This is present in specimens from two outcrops, and in these hardly reaches the rank of an essential constituent. It was the last mineral to crystallize, and is consequently in anhedra, forming the mesostasis. All of the feldspar sections were tested, but no determinative measurements could be made. It is probably very basic.

Apatite.—Apatite is present in small quantity. It exhibits its usual characters.

Spinel.—There is a spinel found in round grains which are included in the olivine (serpentine). It is green in color, and is possibly pleonaste. A second spinel, probably picotite, occurs in small brown grains and octahedra in the olivine.

Calcite.—This mineral, derived partly, if not wholly, from the altering minerals, is found in lenses between the biotite lamellæ and in minute veins which traverse the slide.

Iron ores.—Iron ore is represented by hematite, magnetite, and pyrite. The hematite is in blood-red transparent flakes inclosed in the biotite. Magnetite is included by all of the chief minerals, and is in irregular masses without good crystal development. The iron pyrite is found in good crystals, though not in large quantity, and is scattered here and there through the slides.

PERIDOTITE VARIETIES.

The relative proportions of the minerals described above differ very much, and we have different kinds of rocks corresponding to these mineralogical variations. These kinds are not sharply separated, but are seen under the microscope to grade into one another.

The purest form of peridotite is wehrlite, which is composed essentially of olivine and augite. When, besides these minerals, hornblende is present in large quantities, the rocks belong to the amphibole-peridotite type. In some specimens biotite is almost in sufficient abundance to warrant the naming of them biotite-peridotite. Again, in other specimens feldspar is present in considerable quantity and the rock approaches an olivine-gabbro or olivine-hornblende-gabbro.

WEHRLITE.

This is represented by a coarse-grained rock which is mottled and has a dark-green color. (Specimen 23763, from sec. 22, T. 42 N., R. 31 W., N. 1,500, W. 900 paces.) Under the microscope the mottling is seen to be due to the association of very dark greenish-black serpentine pseudomorphs after olivine with a light-colored augite.

Olivine and augite were present in about equal quantities. They are in anhedra, and therefore must have crystallized at about the same time. The olivine is, with very few exceptions, completely altered to serpentine. Augite has a very poor development. Between the olivine and augite are small quantities of irregular plates of biotite. A few small irregular pieces of a very light colored greenish hornblende were observed. They are intergrown with the pyroxene and give it an imperfect poikilitic texture.

This wehrlite is unquestionably the same as specimen 1247 of the Geological Survey of Wisconsin, described by Dr. A. Wichmann as serpentine, consisting chiefly[1] of serpentine with some unaltered olivine and augite.

AMPHIBOLE-PERIDOTITE.

This variety of peridotite was obtained from the outcrop N. 1,260, W. 200 paces from the southeast corner of sec. 29, T. 42 N., R. 31 W., on the east bank of the Michigamme River. The rock is very coarse grained, and possesses poikilitic texture. It is composed of hornblende, pyroxene, olivine, biotite, and iron oxide. The hornblende equals in quantity all of the other constituents. Some of the hornblende individuals measure 3 cm. in length, and include all of the other constituents except the biotite. The pyroxene and olivine seem to have crystallized at about the same time, as

[1] Microscopical observations of the iron bearing (Huronian) rocks from the region south of Lake Superior, by Dr. Arthur Wichmann, Leipzig, 1876: Geol. of Wisconsin, Vol. III, 1880, p. 619.

they never include each other. They are both, however, included in the hornblende, which with the biotite forms, as it were, the mesostasis. Biotite is present in this specimen in very small quantity, and is essentially the same kind as that above described (p. 252), except that it shows a trifle higher absorption parallel to the cleavage and becomes a yellowish-red. The rock is very fresh and shows scarcely any traces of alteration. This is partly due to the erosive action of the Michigamme River having removed the weathered crust, thus making fresh specimens obtainable.

This rock, from the description just given, would be classified as an amphibole-peridotite, with accessory diallage, bronzite, and biotite. It approaches Williams's cortlandtite. In some specimens the biotite is present in very large quantity, though hardly in sufficient quantity to warrant the designation of any of the rocks as biotite-peridotite.

GRADATIONS OF AMPHIBOLE-PERIDOTITE TO WEHRLITE AND OLIVINE-GABBRO.

There were taken from the same exposure whence the above-described amphibole-peridotite came some specimens which macroscopically can not be distinguished from those of the amphibole-peridotite except in that they are a trifle finer grained. Examined under the microscope, however, we find differences. In some the hornblende is very much reduced in quantity, and varies from the brown kind just described to a light-greenish color, the two being in optical continuity, and the augite and olivine are increased in quantity. These are good types of a wehrlite. In some of the wehrlites there is a variable percentage of feldspar. In certain cases it reaches an amount which would almost warrant the classing of the rock as an olivine-gabbro. Patton described a rock from the same outcrop in which the hornblende still predominated, but in which there was also a certain amount of plagioclase.[1] He called it a hornblende-picrite.[2] According to the terminology here used, if the plagioclase is to be neglected, it would be an amphibole-peridotite.

The thin sections of the feldspathic phase of this rock seem to show that it approaches more closely to a gabbro—that is, to be more feldspathic than the one described by Patton. They certainly contain far less hornblende than his, judging from his description, and more feldspar. The

[1] Mikroscopische Physiographie, by H. Rosenbusch; 3d ed., Stuttgart, Vol. II, 1896, p. 352.
[2] Op. cit., p. 186.

constituents are the same in the two rocks, and with some few modifications his description would answer.

Augite is the chief constituent, and following it, in order of importance, come olivine, hornblende, biotite, and feldspar. The diallagic augite is more automorphic (see fig. *B*, Pl. XLV) as the feldspar increases in quantity. It is the only one of the minerals which shows any marked degree of automorphism. The augite present in the sections which I have studied has a light-brownish color, differing from that described by Patton, which is green to colorless. The augite contains the inclusions occurring in hypersthene, as well as the green (hornblende?) ones already described. It is invariably surrounded by a narrow rim of light-brown hornblende, and includes in places on the edges irregular patches of the same brownish hornblende.

J. Romberg describes the augite in Argentinian gabbros,[1] both with and without olivine, as being almost always surrounded by a rim of *green* hornblende. In one case, however—that of the olivine gabbro from the island of Martin Garcia, in the La Plata River[2]—both brown and green hornblende is present around the augite. The brown hornblende forms part of the periphery of a crystal; the green the remaining portion. Of the green hornblende some is fibrous, and is considered by Romberg to be certainly secondary.

The olivine possesses its usual properties. It is in annedra, with the exception of three or four individuals, which show a fair degree of automorphism. The olivine includes rounded grains of a brown spinel, and is traversed by anastomosing veins of the iron oxide. It shows the usual alteration to serpentine, and the iron oxide is the result of this serpentinization. The olivine is of exceptional interest on account of the fact that it is surrounded by certain zones where it is close to the feldspar (figs. *A* and *B*, Pl. XLVI). The characters of zones observed in sections from this same locality, and which are almost, if not quite, identical with these which I shall proceed to describe, have already been described by Patton.[3] There are two of these zones. An inner one is composed of a mineral which is probably an orthorhombic pyroxene. It was so determined by Patton in

[1] Untersuchungen an Diorit-Gabbro-und Amphibolitgesteinen aus dem Gebiete der Argentiniscnen Republik, by J. Romberg: Neues Jahrbuch für Mineral., BB. IX, 1894, pp. 320–321.

[2] Op. cit., p. 322.

[3] Op. cit., p. 168.

the specimens collected and studied by him. I can obtain no positive proof for or against this statement. If it is an orthorhombic pyroxene, it agrees with the inner zones of related occurrences which have been described by Törnebohm, G. H. Williams, Adams,[1] Romberg,[2] and others. This zone is at any rate composed of a colorless, compact mineral, with high single and moderately high double refraction. Its single refraction is nearly equal to that of olivine. The mineral, as a rule, extinguishes parallel to the lines of cleavage. In a few instances the line of extinction made a scarcely noticeable angle with the cleavage. It is separated from the olivine by a sharp line. At times this inner zone seems to disappear, and at others becomes considerably broader than the average. The width is usually about 0.02 mm., though it becomes at times 0.08 mm.

Outside of this pyroxene zone there is a very much broader zone of light-green hornblende. This is compact, and is in optical continuity with the ordinary brown hornblende, which is the dominant hornblende in the rock. This, in its compact nature and in its relation to the compact brown hornblende of the rest of the slide, differs from the short fibrous actinolite zone ordinarily described as taking part in such "reaction rims." This hornblende zone reaches an extreme width of 0.15 mm. The outer edge of this zone is penetrated by tubular ramifying growths of a colorless mineral, which usually extend inward, perpendicular to the periphery, and which appear to be continuous with the feldspar. This portion of the hornblende rim is about 0.05 mm. wide No such intergrowth of feldspar with the brown hornblende was found, nor have I been able to find elsewhere any description of such an outside zone.[3] However, Romberg describes the interesting occurrence in an olivine-gabbro from the Argentine Republic of zones around the hornblende which are very much like those above described, except that the pseudopodia-like growths, as he describes them, consist of a dark-green spinel instead of a clear white feldspar, as in the Michigan rock.

In some cases, where the olivine and augite are in juxtaposition, the inner orthorhombic pyroxene zone completely surrounds the olivine. The outer hornblende zone, however, surrounds both the augite and the olivine

[1] Uber das Norian oder Ober-Laurentian von Canada, by F. D. Adams: Neues, Jahrbuch für Mineral, BB. VIII, 1893, p. 466, where references to observations made previous to 1893 may be found.

[2] Op. cit., p. 322.

[3] Op. cit., p. 323.

with its orthorhombic pyroxene zone. Where it is in contact with the augite it is the brown variety of hornblende, but is in optical continuity with the green, which is the kind around the olivine and the orthorhombic pyroxene.

Of the remaining mineral constituents brown hornblende is the next one in importance. It has in it patches of inclusions, previously described as occurring in the hornblende of these ultrabasic rocks. It includes also the augite and olivine. This brown hornblende is comparatively rarely found in large plates, but usually as a rim of varying width around the augite and olivine, as already described. Where it occurs in large plates it is in that part of the section which is free from feldspar, and more closely resembles the amphibole-peridotite phase.

The biotite has a cream to light yellowish-brown color, and occurs in irregular plates. The plagioclase feldspar is in irregular broad plates, and forms the mesostasis. The feldspar contains, in not very large quantity, small microlites, which by very high power are translucent and show a greenish tinge. They are supposed to be hornblende microlites.

PROCESS OF CRYSTALLIZATION.

From the relations described as existing between the various minerals it seems that the following stages may be outlined in the progress of the consolidation of this rock. From the coarse even-grained character, and from the fact that neither a fine-grained groundmass nor glass is present, the conclusion seems to be warranted that it crystallized under high pressure and must have, of course, at some time been under very high temperature also.

The augite and olivine were the first and chief silicate constituents to form, and crystallized out of the magma at approximately the same time. The magma soon reached a condition unfavorable for further production of olivine, probably on account of increasing acidity. Immediately around the olivine there was formed, at this stage for a short while, the orthorhombic pyroxene. The monoclinic pyroxene continued to grow during the formation of this orthorhombic variety. Finally, however, the condition was reached when, in place of the monoclinic and orthorhombic pyroxenes, the crystallization of hornblende began.

It is not known what the conditions were which caused the formation

of the hornblende subsequent to and in such intimate association with the pyroxene which it surrounds in zonal growth. An explanation of such occurrences has been attempted by Becke in a recent article,[1] in which the conclusion is reached that the formation of the hornblende and pyroxene depends upon changes in temperature and pressure. His explanation is based upon the facts of occurrence of pyroxene and hornblende in plutonic and effusive rocks, and also upon the well-known fact that under high temperature and atmospheric pressure they can not exist, but when fused recrystallize as pyroxene; and in addition to this, upon the experiments of Von Chrustschoff,[2] who has obtained hornblende at a temperature of 550 C. with the presence of water, under which conditions a high pressure must be developed. However, attention should be called to the fact that his explanation does not take into account other important factors which certainly influence the crystallization of minerals—for example, the chemical composition of the magma and the fusing point and specific gravity of the minerals.

Whatever the factors are which determine its crystallization, the fact is that hornblende began to crystallize from this peridotite magma in the place of pyroxene.

The biotite appears to have been formed at the same time with the hornblende. The production of these two minerals, hornblende and biotite, then continued until the remaining magma had reached the composition of basic feldspar, which then crystallized and now forms the mesostasis.

A zone of orthorhombic pyroxene, succeeded by one of hornblende, has been described as surrounding the olivine in this peridotite. The term *reaction rim* has been applied to similar zones by various observers, but it seems to me that this term is inapplicable to such zones. It is not probable in such a case as this that there is a reaction between the magma and the olivine. Moreover, the zones should not be compared to the *resorption rims* found so commonly in certain effusive rocks, where from the fusion of the hornblende crystals pyroxene has been produced.

Such a zonal growth around the olivine seems to me comparable to such a case as that described by Washington,[3] where colorless diopside

[1] Gesteine der Columbretes; Anhang: Einiges über die Beziehung von Pyroxen und Amphibol in Gesteinen, by F. Becke: Tschermaks mineral. Mittheil., Vol. XVI, 1896, pp. 327–336.

[2] Bull. Acad. imp. sci. St.-Pétersbourg, 1890, p. 13. Cf. Becke, Op. cit., p. 337.

[3] Italian petrological sketches; 4. The Rocca Monfina region, by H. S. Washington: Jour. Geol., Vol. V, 1897, p. 254.

phenocrysts are surrounded by a narrow border of yellowish-green augite, which corresponds to the small augites in the groundmass, or to those cases which are so common in plutonic rocks—even in this rock described—where hornblende is found surrounding the pyroxene.

A general explanation which would account for the successive crystallization of hornblende and pyroxene in this rock should be applicable to such a zonal growth as occurs around the olivine, taking into consideration, of course, the probability that a factor of slight importance in the one case may be the controlling factor in the other. Such occurrences seem clearly to indicate a change in the chemical composition of the magma as the chief factor in the crystallization of the different minerals, in the pressure, in the temperature, and also in other factors, either one alone or more of these combined.

ANALYSIS OF PERIDOTITE.

The peridotite just described was analyzed by Dr. H. N. Stokes of the United States Geological Survey, and his results are here given (No. 1):

Analysis of peridotite.

	1 (23353).	2 (22981).
SiO_2	44.99	37.36
TiO_2	.97	.79
Al_2O_3	5.91	4.76
Cr_2O_3	.25	.62
Fe_2O_3	3.42	6.61
FeO	8.30	6.12
MnO	Trace.	Trace.
NiO	....	.04
CaO	8.79	1.19
MgO	21.02	31.11
K_2O	.74	Trace.
Na_2O	.91	
H_2O at 110°	.63	.65
H_2O above 110°	3.19	10.37
P_2O_5	.05	.06
CO_2	Trace (?).	None.
Total	99.17	99.68

It will be seen from the analysis that the silica is somewhat too high for the typical peridotites. This same fact is also emphasized by the tendency manifested in some facies of the peridotite for feldspar to develop, and thus for transitions to norite and gabbro to be produced.

With this analysis of the peridotite there is placed for comparison the analysis (No. 2) by Dr. H. N. Stokes of the picrite-porphyry already described. The close resemblance chemically becomes at once manifest, although the latter is more nearly a typical peridotite in composition. It can not be denied that possibly this picrite is but a further differentiation product of the same magma to which the peridotites belong, although its occurrence is so remote from these that it is impossible to connect them in the field.

PERIDOTITE FROM SEC. 22, T. 42 N., R. 31 W., N. 1,990, W. 150.

Just west of the northeastern corner of sec. 22, T. 42 N., R. 31 W., there is a bold outcrop of hornblende gabbro, which is cut by a dike, about 10 feet wide, of a very massive, coarse, granular black peridotite. Macroscopically one can readily distinguish in the peridotite flakes of biotite, poikilitic plates of hornblende, and a smaller amount of white feldspar. Under the microscope the constituents are, in order of importance: Hornblende, augite, feldspar, biotite, bronzite, olivine, magnetite, and quartz.[1]

Hornblende.—This is the rich brown kind, full of inclusions, grading into the green variety which was described on p. 234 as occurring in the gabbros of this district. It is present in anhedra inclosing biotite, pyroxene, and olivine.

Pyroxene.—This is represented by monoclinic and orthorhombic varieties. The monoclinic pyroxene, augite, is most abundant, and is in light-yellow to pink-colored anhedra, except where it touches the feldspar; there the augite is automorphic, and is surrounded by a narrow border of light-brown hornblende.

The orthorhombic pyroxene is present in a few anhedra, which are colorless or have a faint cream tint. It is presumed to be bronzite.

Feldspar.—This fills the interspaces between the other constituents, and occurs in grains which are polysynthetically twinned after the albite law.

[1] Only one section has been prepared from this specimen, and it may not give a correct idea of the true proportion of these minerals in the rock mass. In the macroscopical examination of the hand specimen the biotite seemed to be subordinate only to the hornblende.

Measurements gave a symmetrical extinction of 32 each side of the twinning plane on zone $\perp 010$. I therefore conclude the feldspar to be labradorite.

Biotite.—This is the ordinary yellow to brownish kind, and is in irregular plates. It shows its usual characters and is included in the hornblende.

Magnetite.—This mineral occurs in crystals and grains, included in all the other constituents.

Quartz.—A few grains of quartz were found associated with the feldspar. The presence of dihexahedral liquid inclusions easily gave a clew to the orientation of the grains.

The rock composed of the above-described minerals offers a good illustration of that gradation which is one of the fundamental laws of nature and is nowhere better exemplified than in the rocks. On the one hand, from its texture and from the presence of the dominant hornblende, with the small quantity of quartz, this rock may perhaps be considered to be closely related to the diorites. On the other hand, the presence of the pyroxene and olivine seems to point toward its connection with a gabbro.

Its geological occurrence points most satisfactorily toward its correspondence in age and its intimate relationship to the peridotites of the district. The predominance of the bisilicates indicates it to be of very basic character, and for these reasons I have called it "peridotite," although I have not succeeded in getting an analysis to prove its ultrabasic nature.

RELATIONS OF PERIDOTITES TO OTHER ROCKS.

The peridotites occur in such small quantity that general conclusions concerning their relations to other rocks occurring in their vicinity are scarcely warranted. However, from the fact that they are so intimately associated with the gabbro—cutting it in two cases where the contact was observed—and from the fact that among the peridotites themselves certain phases approach in mineralogical composition certain of the gabbros (see p. 254), it seems advisable to conclude that they represent ultrabasic differentiation products of the same magma from which the gabbro types were derived. The inappreciable differences in grain between the portion of the rock nearest the contact between these basic rocks and the gabbros and those farther away can be explained by supposing their intrusion to have taken place while the main mass of the gabbro retained considerable heat and thus prevented their rapid cooling.

AGE OF PERIDOTITES.

The only statement which can be made concerning the age of the peridotite dikes is that they are younger than some of the gabbros, and that, not having suffered the deformation of the pre-Keweenawan orogenic movements, they are Keweenawan or post-Keweenawan.

GENERAL OBSERVATIONS ON THE ABOVE SERIES.

TEXTURAL CHARACTERS OF THE SERIES.

There are represented in the above series rocks with moderately fine grain as well as those of very coarse grain. They vary from those with parallel texture, through those with porphyritic, poikilitic, and ophitic texture, to those with granular texture. There is, however, throughout a clear preponderance of the medium to coarse granular rocks. The rocks are evidently not of effusive character, though some possess the textures prevalent in effusive rocks.

The order of crystallization of the minerals in the rocks of granular texture, excluding the iron ores and the accessory minerals, is as follows. The order in the imperfectly ophitic and porphyritic rocks is not considered, as those are rather exceptional occurrences.

In the lists those minerals are hyphenated of which it has not been possible to determine accurately the order of crystallization. It seems that either they were formed at the same time or, in some cases, their formation has overlapped. In such cases the one placed first is the one presumed to have begun its crystallization first.

Diorite.	Gabbro and hornblende-gabbro.	Bronzite-norite.	Peridotite.
Hornblende.	Olivine.	Bronzite.	Olivine.
Biotite.	Monoclinic pyroxene.	Monoclinic pyroxene.	Orthorhombic pyroxene.
Plagioclase.	Biotite-hornblende.	Biotite-hornblende.	Monoclinic pyroxene.
Microcline.	Plagioclase.	Plagioclase.	Biotite-hornblende.
Orthoclase-quartz.			Plagioclase.

For the entire series the order may be arranged as follows: Olivine, bronzite, monoclinic pyroxene, mica-hornblende, plagioclase, orthoclase, quartz. This is the same order that is exhibited by the most basic rock represented in the series, the peridotite, so far as this rock contains the minerals.

The order of crystallization of the minerals throughout the series is due to their relative solubility in the eruptive magma. Among various factors affecting solubility the fusion point of the chemical compounds constituting the different minerals, the temperature of the magmas, and the pressure under which the minerals crystallized, are important. The porphyritic and the ophitic textured rock facies, having crystallized under different conditions of pressure and of temperature from those under which the granular rocks were formed, show, as is to be expected, a different order of crystallization of minerals.

CHEMICAL COMPOSITION OF THE SERIES.

In the following tables there are reproduced the analyses which have been obtained of the various types. They are arranged according to diminishing acidity. Nos. 1 and 4 were analyzed by Dr. H. N. Stokes, Nos. 2 and 3 by Mr. George Steiger, both of the United States Geological Survey:

TABLE I.—*Analyses of Crystal Falls rocks.*

	1 (26023).	2 (23354).	3 (23755).	4 (23353).
SiO_2	58.51	49.80	48.23	44.99
TiO_2	.72	.79	1.00	.97
Al_2O_3	16.32	19.96	18.26	5.91
Cr_2O_3	None.			.25
Fe_2O_3	2.11	6.32	1.26	3.42
FeO	4.43	.49	6.10	8.30
MnO	Trace.			Trace.
NiO	None.			None.
CaO	3.92	11.33	9.39	8.79
MgO	3.73	7.05	10.84	21.02
K_2O	4.08	.61	.73	.74
Na_2O	3.11	2.22	1.34	.91
H_2O at 110°	.23	100°— .13	100°— .26	110° .63
H_2O above 110°	2.00	100°+1.71	100°+2.00	110°+3.19
P_2O_5	.30	.07	.07	.05
CO_2	None.	.15	.43	Trace. (?)
Total	99.46	100.63	99.91	99.17

(1) Mica-diorite (quartzitic); (2) Hornblende-gabbro; (3) Norite; (4) Peridotite (wehrlite).

TABLE II.—*Percentages of chief oxides reduced to 100.*

	1.	2.	3.	4.
SiO_2	60.36	50.52	49.64	47.33
TiO_2	.75	.80	1.03	1.02
Al_2O_3	16.83	20.25	18.79	6.22
Fe_2O_3	2.17	6.41	1.30	3.60
FeO	4.57	.50	6.28	8.73
CaO	4.04	11.50	9.67	9.25
MgO	3.85	7.15	11.16	22.11
K_2O	4.21	.62	.75	.78
Na_2O	3.21	2.25	1.38	.96

TABLE III.—*Atomic proportions of metals.*

Si	55.85	46.53	45.27	42.48
Ti	.53	.56	.71	.70
Al	18.41	22.03	29.26	6.60
Fe	5.08	.834	5.70	9.02
Ca	4.04	11.42	9.51	8.98
Mg	5.32	9.85	15.22	29.67
K	4.99	.74	.88	.91
Na	5.78	4.04	2.45	1.67

The analyses show that all of the rocks contain a moderately large amount of water. Nevertheless, they are sufficiently well preserved to warrant a discussion of their analyses for classification purposes. This is especially true of No. 4, which is remarkably fresh for so basic a rock.

The chief rock-making oxides in the above analyses appear in Table II reduced to 100. The molecular proportion of these oxides was then obtained. From these data the atomic proportions of the metals were derived, and are given in Table III. These calculations were kindly made for me by Mr. V. H. Bassett, assistant in the chemical laboratory of the University of Wisconsin.

If we examine Table II we see that, in passing from the more acid to the basic end of the series, in correspondence with this decrease in silica the alumina increases rapidly, then decreases until it reaches the extreme basic rock, when it drops suddenly to 6.22 per cent. The analyses also show an increase in iron, which is best brought out in Table III. The alkalies decrease with diminishing silica, whereas the MgO, which for rocks of this character is very characteristic, shows a decided increase. Within the gabbro-norite-peridotite series (Nos. 2, 3, and 4) the lime shows

a constant diminution corresponding to the increasing magnesian character of the rocks. The potash increases as the soda shows a decrease.

The rocks represented by the analyses are believed to belong to a series ranging from a diorite on the one hand, through hornblende-gabbro and norite, to peridotite on the other. It should be borne in mind that the diorite is somewhat exceptional, representing a gradation toward the orthoclase rocks. On the acid side of the series the microscope also shows variations to tonalitic and even granitic rocks very rich in quartz and orthoclase, consequently much more acid in character than the diorite represented in the analysis.

It is a difficult matter to estimate quantitatively the amount of the one or the other kind of rock present in the Crystal Falls district. We are thus prevented from drawing from the predominance of the one kind or the other the conclusion that those represented in the minority are the results of the differentiation of a magma most nearly resembling in its original constitution that which predominates. Moreover, since the analyzed rock types were not selected as representatives of the extremes of the process of differentiation, it would not be wise to endeavor to give the mean composition of the parent magma from the analyses of the differentiation products which have been presented. The main thesis, however, is established that the separation of a magma into the various products described has taken place, as is indicated by the relations in the field, and as has been shown by the microscopical and chemical analyses.

RELATIVE AGES OF ROCKS OF THE SERIES.

Study of the relative periods of eruption of the various rocks results in the determination of the hornblende-gabbro as the rock which first reached its present position. It was followed in the acid part of the series by the diorite, which in one place cuts it. The diorite is cut by the diorite-porphyry.

Along the basic series the order has been determined as hornblende-gabbro, gabbro, bronzite-norite, peridotite.

In general the forces of differentiation seem to have been active in two directions, tending toward increasing acidity and increasing basicity of the products of differentiation, thus agreeing with the law of succession of igneous rocks as propounded by Iddings.[1]

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[1] The origin of igneous rocks, by J. P. Iddings: Bull. Philos. Soc. Wash., Vol. XII, 1892, p. 195.

PLATE XIX.

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PLATE XIX.

FIG. *A*.

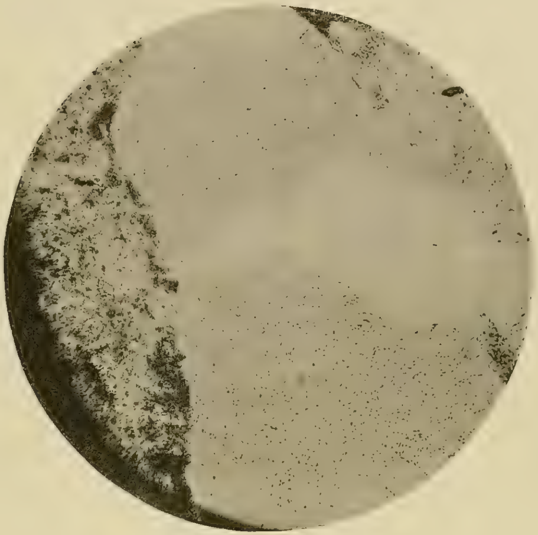
(Sp. No. 32756. Without analyzer, x 90.)

Photomicrograph of fractured quartz phenocryst from a rhyolite-porphyry. It includes numberless liquid inclusions, which diminish in quantity as the distance from the plane of fracture is increased, thus indicating their close connection with the fracturing of the quartz. The fracture in the quartz phenocryst continued into the groundmass, as may be seen on the left-hand side of the figure. It has been healed with secondary quartz. (Described, p. 82.)

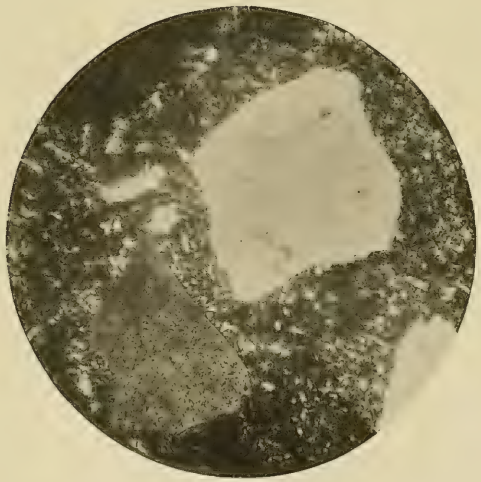
FIG. *B*.

(Sp. No. 32914. With analyzer, x 47.)

Photomicrograph of a section of rhyolite-porphyry, designed to show the rhombohedral parting, which is very common in many of the quartz phenocrysts. (Described, p. 82.)



(*A*)



(*B*)

(**A**) INCLUSIONS IN A FRACTURED QUARTZ PHENOCRYST.

(**B**) RHOMBOHEDRAL PARTING IN A QUARTZ PHENOCRYST.

THE MERIDEN GRAVURE CO.

PLATE XX.

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PLATE XX.

Fig. *A*.

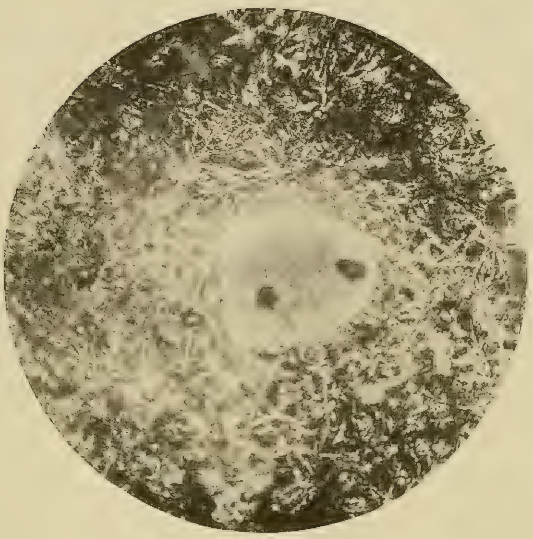
(Sp. No. 32119. With analyzer, x 90.)

Micropoikilitic rhyolite-porphyry, showing the peculiar texture of the zones which invariably surround the quartz phenocrysts in sections in which the texture occurs. The same texture prevails in the groundmass. The irregular white areas which are continuous with the quartz phenocrysts and are connected with each other represent quartz. Disconnected dark and light areas between the quartz stringers are feldspar grains. These do not possess uniform orientation; hence the texture is not micropegmatitic. (Described, p. 84.)

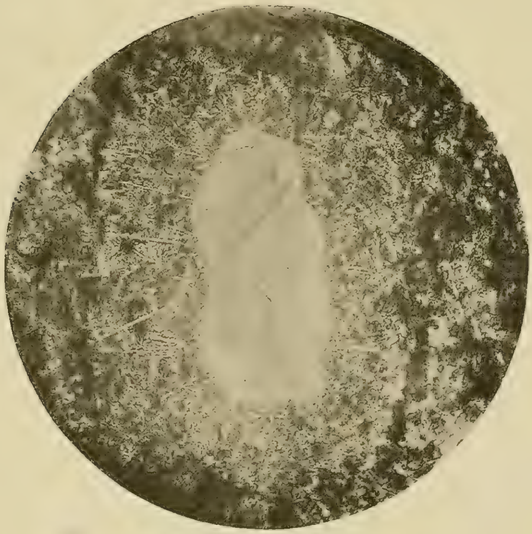
Fig. *B*.

(Sp. No. 32137. With analyzer, x 90.)

Photomicrograph of micropoikilitic rhyolite-porphyry. In this rhyolite-porphyry the micropoikilitic texture is much finer than that represented in Fig. *A*, and the quartz in the zones shows a tendency toward spherulitic development. Owing to the extreme fineness of grain it is difficult to distinguish the quartz and feldspar in many cases. The greater part of the light areas shown in the photomicrograph are quartz. The dark areas between the quartz, and also some of the lighter areas, represent irregular pieces of feldspar. (Described, p. 84.)



(*A*)



(*B*)

MICROPOIKILITIC RHYOLITE-PORPHYRY.

THE MERIDEN GRAVURE CO.

PLATE XXI.

PLATE XXI.

Fig. *A*.

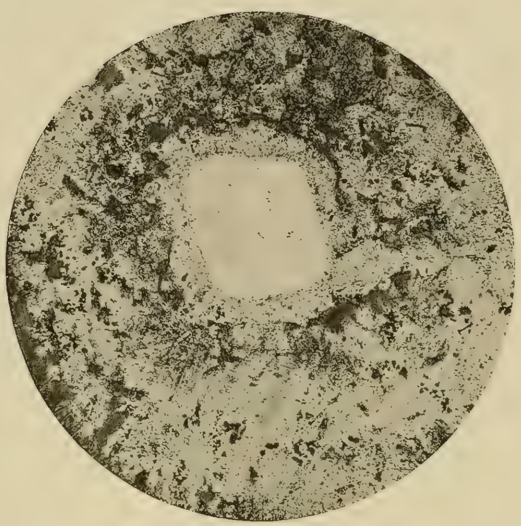
(Sp. No. 32136. Without analyzer, x 90.)

Rhyolite-porphyry with aureoled phenocrysts. The finest-grained type of micropoikilitic texture is here represented. The groundmass of this porphyry consists of rounded areas of material ("quartz épongeuse"), corresponding to that forming the zones around the phenocrysts. Between these areas there may be found in places small feldspars. These photomicrographs, represented in figs. *A* and *B*, Pl. XX, and in this figure, show every gradation in the micropoikilitic texture, from that which is with difficulty distinguishable as such to the coarser-grained unmistakable variety. (Described, p. 85.)

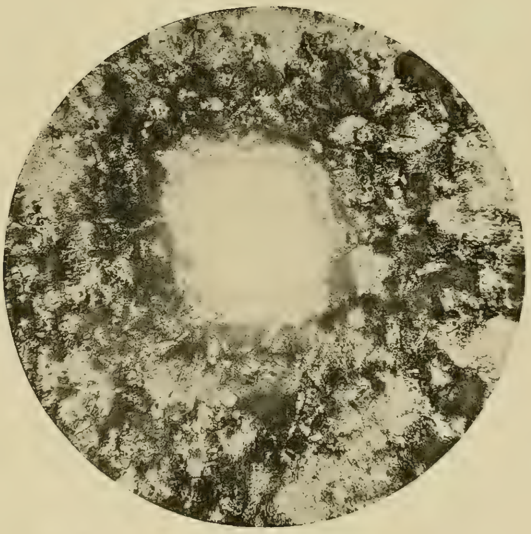
Fig. *B*.

(Sp. No. 32136. With analyzer, x 90.)

Rhyolite-porphyry with aureoled phenocrysts. This is the same section as is represented above when viewed between crossed nichols. The texture of the groundmass is brought out somewhat better. The feldspars especially become more noticeable. For instance, one Carlsbad twin may be seen at the lower right-hand corner of the phenocryst partly indenting the aureole. Other feldspars may be noticed through the groundmass. In other portions of the section from which this photomicrograph is taken the quartz phenocrysts have no aureoles and the groundmass possesses an imperfect microgranitic texture. This figure brings out clearly the gradation toward that texture. (Described, p. 85.)



(*A*)



(*B*)

MICROPOIKILITIC RHYOLITE-PORPHYRY.

THE MERIDEN GRAVURE CO.

PLATE XXII.

PLATE XXII.

Fig. *A.*

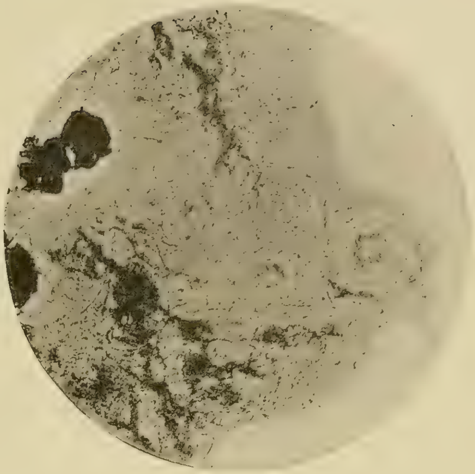
(Sp. No. 32732. Without analyzer, x 18.)

Aporhyolite showing beautifully developed perlitic parting. The perlitic cracks are brought out clearly by the chlorite which has accumulated in them. (Described, p. 87.)

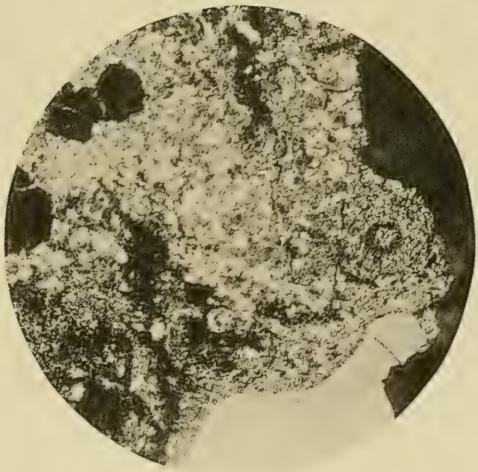
Fig. *B.*

(Sp. No. 32732. With analyzer, x 18.)

Aporhyolite showing perlitic parting, when viewed between crossed nicols. The groundmass resolves itself into a fine-grained mosaic of quartz and feldspar, showing micrographitic characters. The perlitic parting is thereby almost completely obscured. (Described, p. 87.)



(*A*)



(*B*)

(*A*) PERLITIC PARTING IN APORHYOLITE.

(*B*) PERLITIC PARTING IN APORHYOLITE BETWEEN CROSSED NICOLS.

THE MERIDEN GRAVURE CO.

PLATE XXIII.

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PLATE XXIII.

Fig. *A*.

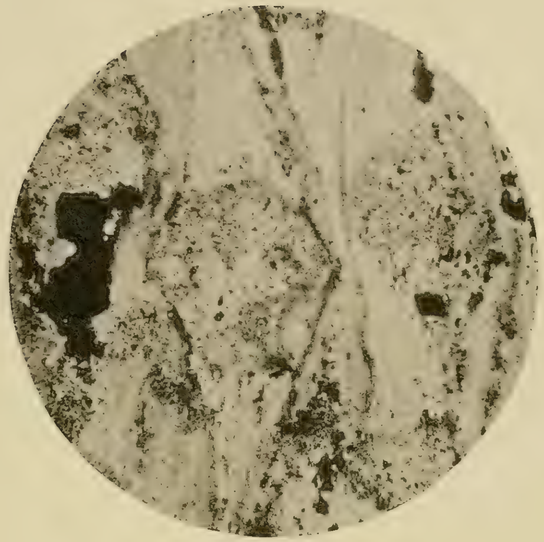
(Sp. No. 22953. Without analyzer, x 38.)

Rhyolite-porphyry rendered schistose by crushing. Granulation of the feldspars and the resulting production of schistose aggregates of secondary quartz, feldspar, and sericite is here shown. The two large areas shown near the center of the figure were formerly occupied entirely by feldspar. The greater portion of this has now become altered, mere remnants of the original remaining. This secondary aggregate has especially well-developed parallelism. (Described, p. 93.)

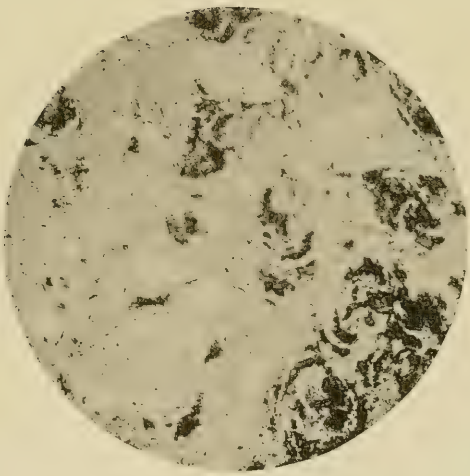
Fig. *B*.

(Sp. No. 32726. With analyzer, x 18.)

Photomicrograph of aporhyolite-porphyry breccia showing the fractured character of the quartz and feldspar. Certain portions of the section show the perlitic parting, with accumulations in these areas of chlorite. (Described, p. 93.)



(*A*)



(*B*)

(*A*) SCHISTOSE RHYOLITE PORPHYRY.

(*B*) APORHYOLITE BRECCIA.

THE MERIDEN GRAVURE CO.

PLATE XXIV.

PLATE XXIV.

Fig. *A*.

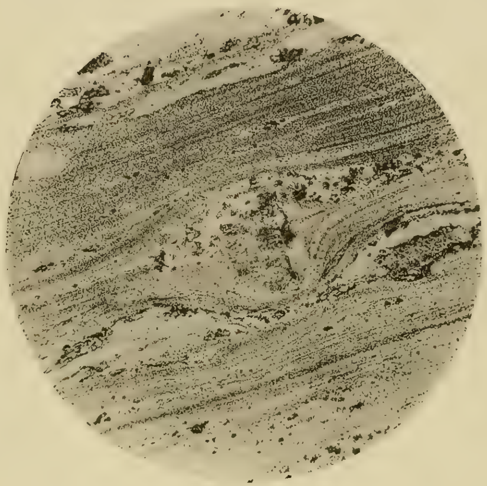
(Sp. No. 22968. Without analyzer, x 18.)

Schistose rhyolite-porphyry with well-developed flowage structure. A feldspar phenocryst which has been more or less rounded by crushing, occupies the center of the figure. There is also shown in the upper left-hand quadrant of the figure a small crushed quartz phenocryst. (Described, p. 93.)

Fig. *B*.

(Sp. No. 22968. With analyzer, x 18.)

When the section represented in fig. *A* is viewed between crossed nicols, the crushed character of the feldspar phenocrysts is thereby well brought out. The minutely granular character of the groundmass is also well shown. (Described, p. 93.)



(A)

(B)

(A) SCHISTOSE RHYOLITE PORPHYRY.

(B) SCHISTOSE RHYOLITE PORPHYRY BETWEEN CROSSED NICOLS.

THE MERIDEN GRAVURE CO.

PLATE XXV.

PLATE XXV.

Fig. *A.*

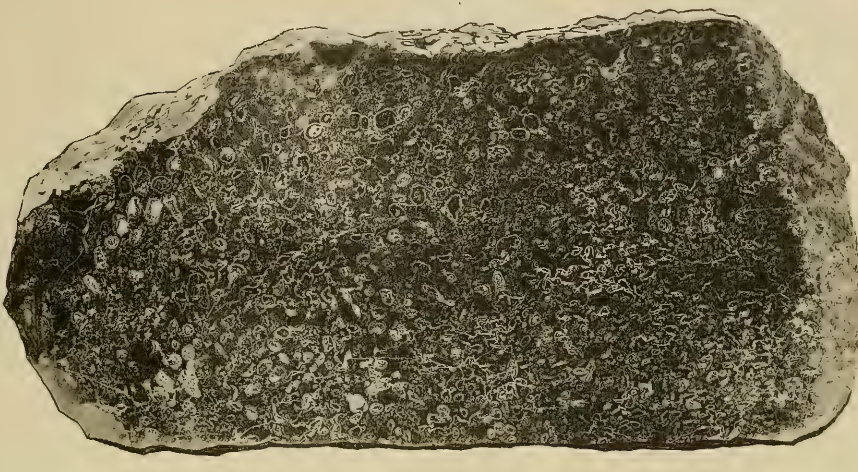
(Sp. No. 32116.)

Photograph, with very slight enlargement, of the polished surface of a very fine grained but very amygdaloidal basalt. The amygdules are of irregular shape, but in general with a rounded or tubular character. The original cavities have been filled with chlorite and quartz. The chloritic amygdules are the most common. A few of the white quartz amygdules may be seen on the left-hand side of the figure. It should be noted that owing to the softness of the chlorite some of the amygdules have become impregnated with the powder used in polishing the specimen. This could not be removed, and in many cases may be seen filling as well as outlining the chlorite amygdules. (Described, p. 95.)

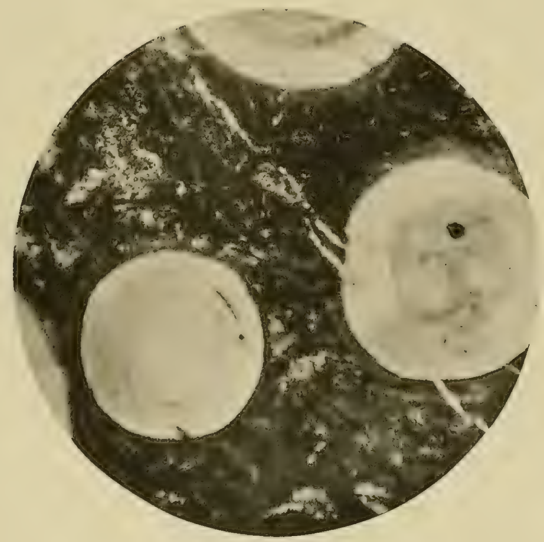
Fig. *B.*

(Sp. No. 32903. Without analyzer, x 18.)

Photomicrograph of a section of the fine grained, possibly vitreous, amygdaloidal basalt represented in fig. *A* of Pl. XXVII. The amygdules consist of chlorite, quartz, and feldspar. The greatest interest centers in the groundmass. This consists of a fine felt of chlorite with minute epidote grains. Traversing this, one sees in places delicate flowage lines. This is believed to represent a once vitreous basalt. (Described, p. 102.)



(*A*)



(*B*)

(*A*) AMYGDALOIDAL BASALT.
(*B*) AMYGDALOIDAL BASALT.

THE MERIDEN GRAVURE CO.

PLATE XXVI.

PLATE XXVI.

Fig. *A*.

(Sp. No. 32541. Without analyzer, x 18.)

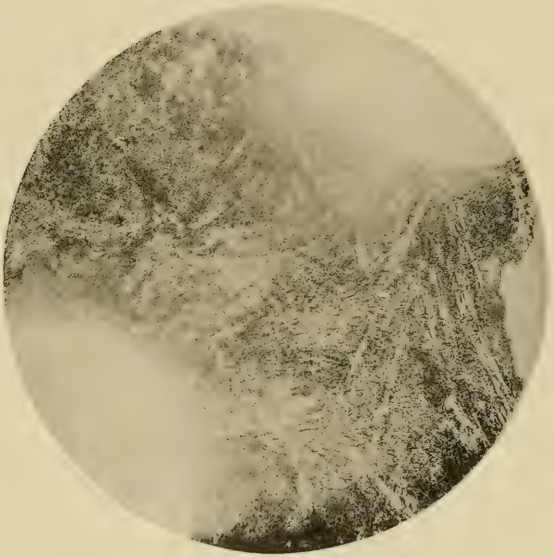
Fine-grained amygdaloidal basalt. The only recognizable original constituent in the groundmass is the feldspar in microlites which most commonly fringe out at the ends. They are not infrequently arranged in sheaf-like aggregates. These are best seen with high-power objectives. The major portion of the groundmass consists of a fine felt of chlorite, with minute grains of epidote. It is considered to have resulted from the alteration of a vitreous base. The amygdules consist of calcite. (Described, p. 99.)

Fig. *B*.

(Sp. No. 32541. Without analyzer, x 35.)

Portion of section from which fig. *A* was taken viewed with a high power. In this the sheaf-like aggregates of feldspar can be seen. (Described, p. 99.)

(*A*)



(*B*)

(*A*) AMYGDALOIDAL BASALT.

(*B*) SHEAF-LIKE FELDSPAR AGGREGATES.

THE MERIDEN GRAVURE CO.

PLATE XXVII.

PLATE XXVII.

Fig. *A*.

(Sp. No. 32903. Natural size.)

Reproduction of a very fine grained, possibly vitreous, amydaloidal basalt. The amygdaloidal cavities show very little contortion. The amygdules consist of white quartz, pink feldspar, and dark-green chlorite. Compare this figure with photomicrograph fig. *B*, Pl. XXV. (Described, p. 102.)

Fig. *B*.

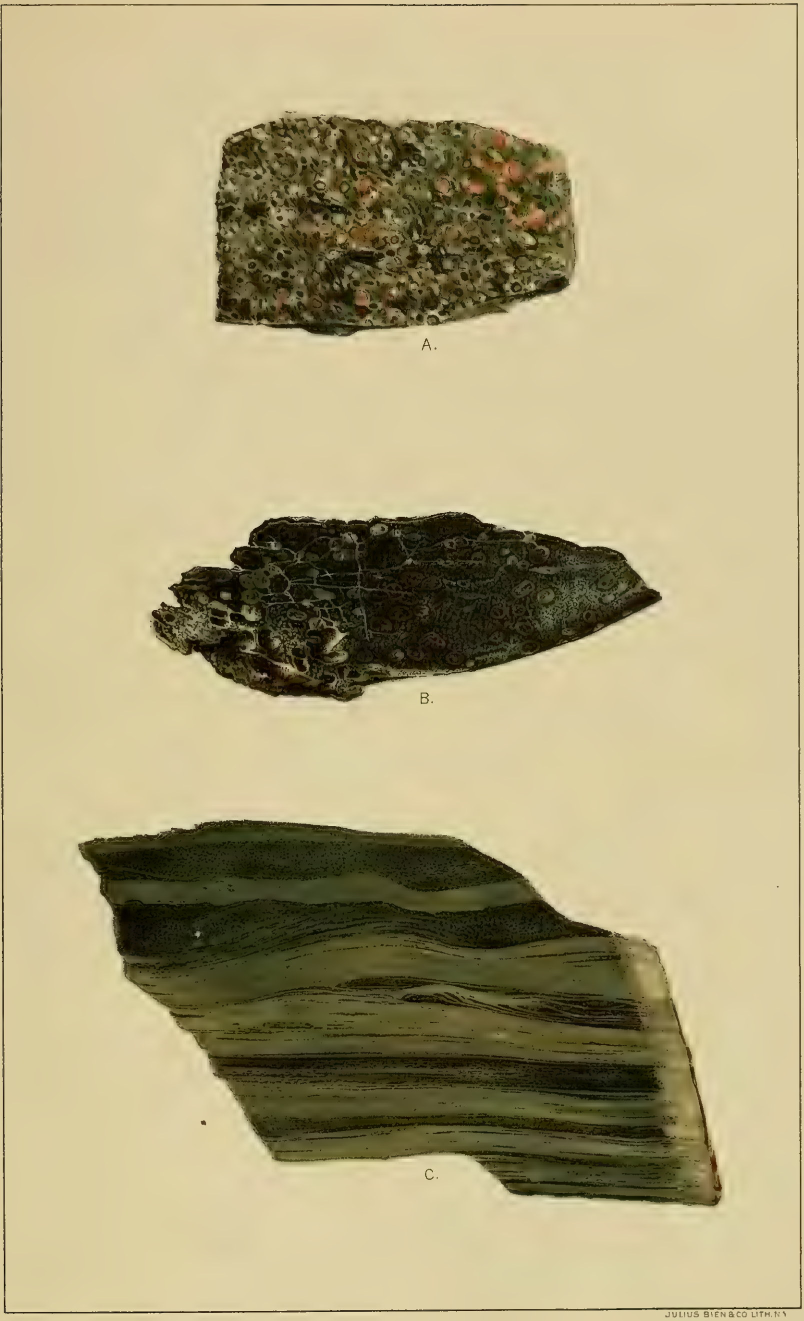
(Sp. No. 32910. Natural size.)

Colored reproduction of the pseudoamygdaloidal phase of the siderite-quartz matrix which occurs in places between the ellipsoids. The original matrix was first replaced in the zone of weathering by siderite. Deep burial of the rock resulted in the mashing of the siderite and the subsequent replacement of a great portion of it by silica, leaving a few oval areas unsilicified. Brought into the zone of weathering again by erosion, these siderite areas are removed on the weathered surface giving a scoriaceous appearance to it, as may be seen on the figure. (Described, p. 135.)

Fig. *C*.

(Sp. No. 33507. Natural size.)

Fine-grained volcanic clastic. The water-deposited character of this specimen is unquestionable. It can be traced in the field down into a coarse bowlder conglomerate. The fragmental nature can only be seen under the microscope in the coarser-grained portions. The finer-grained material represents apparently the excessively fine-grained mud derived from the trituration of the coarser fragments. The eolian-deposited sands and dust have essentially the same appearance as the specimen here represented. The microscope, however, shows the very angular character of the fragments in the coarser-grained portions. The very fine eolian-deposited dust can not be distinguished from that which has been deposited through water. It is sometimes very difficult to determine the nature of rocks of this fine-grained character. (Described, p. 144.)



JULIUS BIEN & CO LITH. N.Y.

A. AMYGDALOIDAL BASALT.
B. PSEUDO-AMYGDALOIDAL MATRIX OF ELLIPSOIDAL BASALT
C. VOLCANIC CLASTIC.

PLATE XXVIII.

PLATE XXVIII.

Fig. *A*.

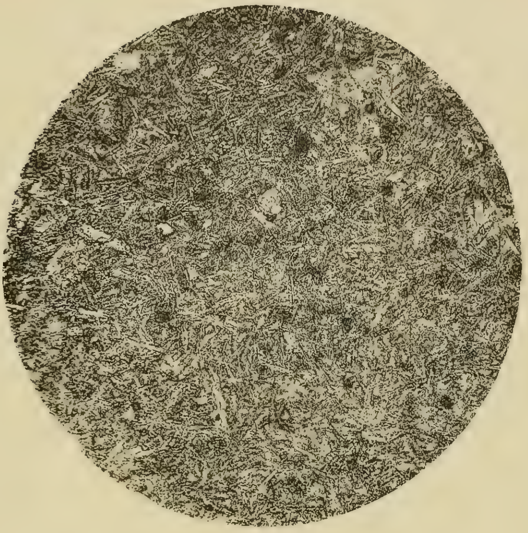
(Sp. No. 32909c. Without analyzer, x 35.)

Photomicrograph of section of fine-grained basalt with well-developed igneous texture. The feldspar outlines are now occupied chiefly by flakes of muscovite and grains of zoisite. (Described, p. 127.)

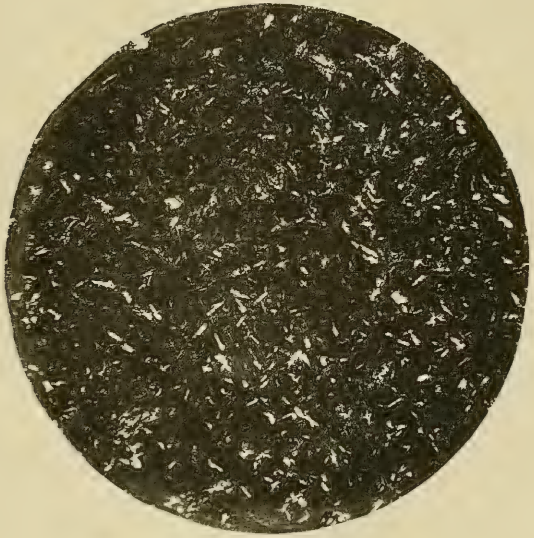
Fig. *B*.

(Sp. No. 32909c. With analyzer, x 35.)

Photomicrograph of the same section when viewed between crossed nicols, showing the obliteration of the igneous texture. The lath-shaped mineral is muscovite. (Described, p. 127.)



(A)



(B)

(A) BASALT SHOWING CHARACTERISTIC TEXTURE.

(B) BASALT SHOWING OBLITERATION OF TEXTURE BETWEEN CROSSED NICOLS.

THE MERIDEN GRAVURE CO.

PLATE XXIX.

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PLATE XXIX.

FIG. *A*.

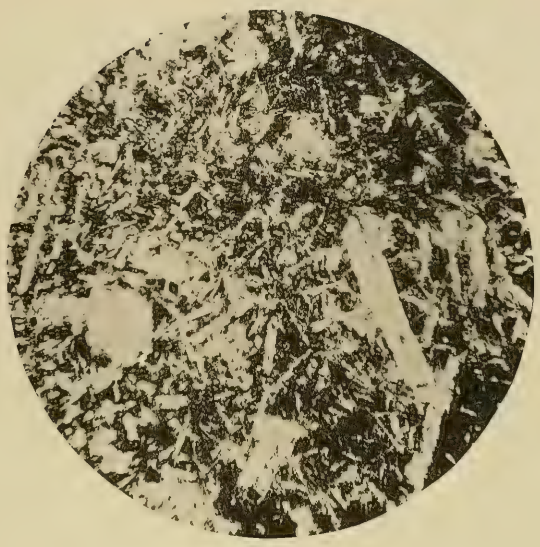
(Sp. No. 32582. Without analyzer, x 38.)

Photomicrograph showing the normal igneous texture of a basalt. The area formerly occupied by the feldspar substance is now occupied by a granular aggregate of various minerals. (Described, p. 127.)

FIG. *B*.

(Sp. No. 32582. With analyzer, x 38.)

The same section of basalt when viewed between crossed nicols. The only indication of an igneous texture is shown by the amygdules present. The igneous texture of the rock is completely concealed as soon as the aggregates occupying the feldspar areas break up into their constituent grains. (Described, p. 127.)



(*A*)

(*B*)

(*A*) BASALT SHOWING CHARACTERISTIC TEXTURE.

(*B*) BASALT SHOWING OBLITERATION OF TEXTURE BETWEEN CROSSED NICOLS.

THE MERIDEN GRAVURE CO.

PLATE XXX.

PLATE XXX.

Fig. *A*.

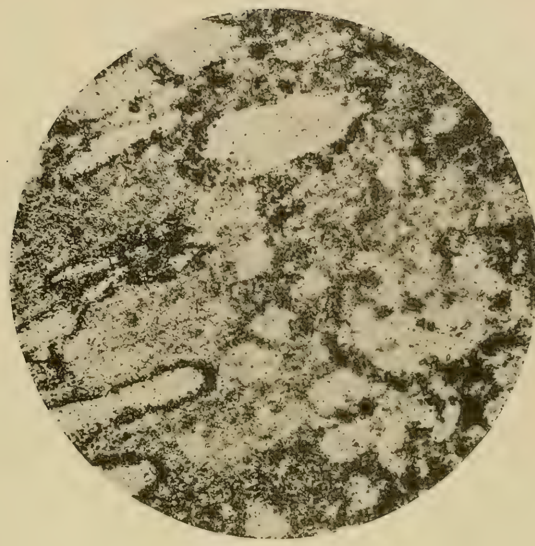
(Sp. No. 33313. Without analyzer, x 38.)

Photomicrograph of a section of basalt from a pyroclastic showing in ordinary light a distinctly amygdaloidal character. The alteration of the basalt has, however, reached such a stage that the groundmass materials have for the most part been completely altered, with the production of porphyritic rhombohedra of calcite and plates of muscovite, which may be seen in abundance in the lower right-hand side of the figure. (Described, pp. 129, 145.)

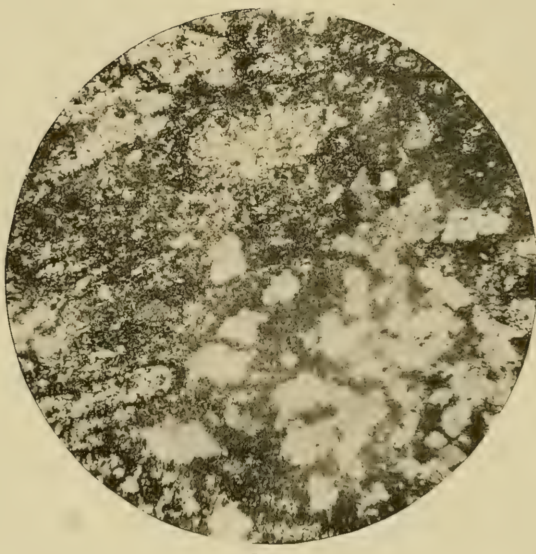
Fig. *B*.

(Sp. No. 33313. With analyzer, x 38.)

Photomicrograph of the same section of basalt, showing in ordinary light a distinctly amygdaloidal character when viewed between crossed nicols. The igneous texture is almost completely obliterated by secondary products. The secondary calcite and muscovite stand out very sharply from the very fine grained groundmass. (Described, p. 129.)



(A)



(B)

(A) BASALT FRAGMENT IN A PYROCLASTIC SHOWING AMYGDALOIDAL TEXTURE.

(B) BASALT FRAGMENT SHOWING OBLITERATION OF THIS TEXTURE BETWEEN CROSSED NICOLS.

THE MERIDEN GRAVURE CO.

PLATE XXXI.

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PLATE XXXI.

Fig. *A*.

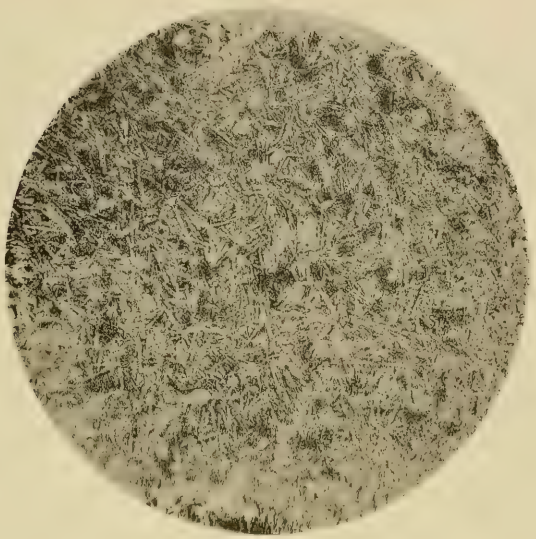
(Sp. No. 32909c. Without analyzer, x 35.)

Photomicrograph illustrating the igneous texture of the basalt from the center of an ellipsoid. This has already undergone advanced alteration, and the feldspars have been replaced by a granular aggregate of calcite, sericite, chlorite, epidote, quartz, and albite. With advancing alteration the igneous texture is destroyed, and infiltrated calcite becomes more prominent. The photomicrograph shows in the lower left-hand corner a portion of the section in which a large quantity of calcite is present. (Described, p. 131.)

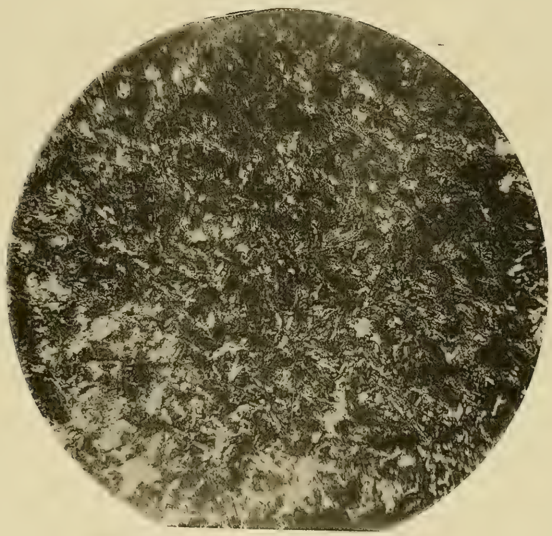
Fig. *B*.

(Sp. No. 32909c. With analyzer, x 35.)

Photomicrograph illustrating the igneous texture of the basalt from the center of an ellipsoid, when viewed between crossed nicols. The igneous texture is almost completely destroyed by the breaking up of the secondary aggregates. (Described, p. 131.)



(*A*)



(*B*)

(*A*) BASALT.

(*B*) BASALT SEEN BETWEEN CROSSED NICOLS.

THE MERIDEN GRAVURE CO

PLATE XXXII.

PLATE XXXII.

FIG. *A*.

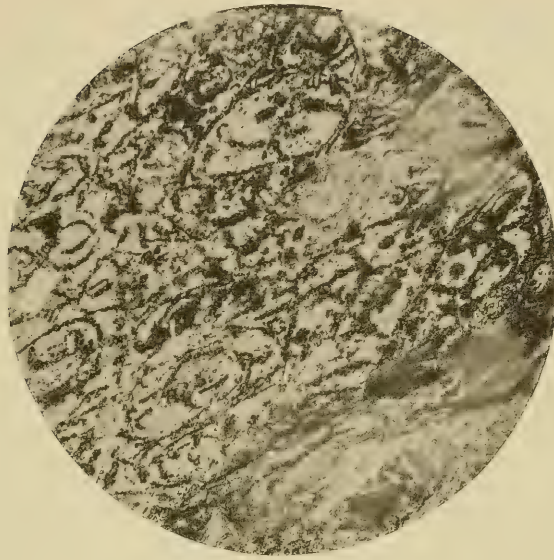
(Sp. No. 23645. Without analyzer, x 35.)

Perlitic parting in a fragment from a basalt tuff. The perlitic cracks are marked by accumulations of epidote grains. The remainder of the fragment consists of an exceedingly fine chlorite felt, with here and there a small feldspar microlite embedded in it. This was probably a fragment of basalt glass. (Described, p. 138.)

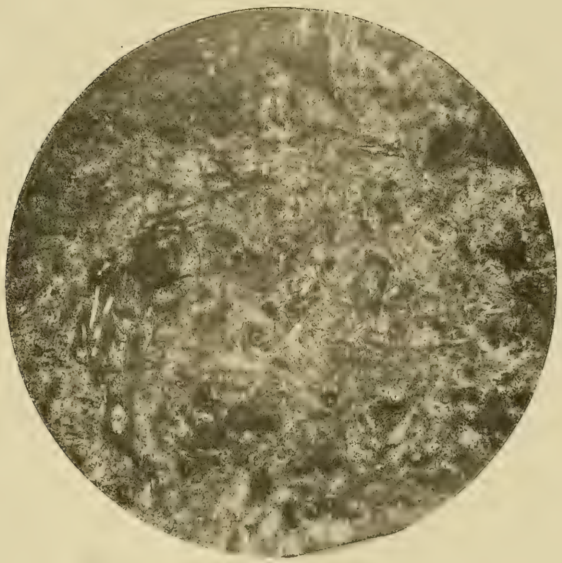
FIG. *B*.

(Sp. No. 23646. Without analyzer, x 35.)

Photomicrograph of a section of basalt tuff. The illustration shows the sickle-shaped bodies which are characteristic for the fine eolian-deposited volcanic ejectamenta. (Described, p. 142.)



(*A*)



(*B*)

(*A*) PERLITIC PARTING IN BASALT (GLASS?).

(*B*) TUFF.

THE MERIDEN GRAVURE CO.

PLATE XXXIII.

PLATE XXXIII.

Fig. *A*.

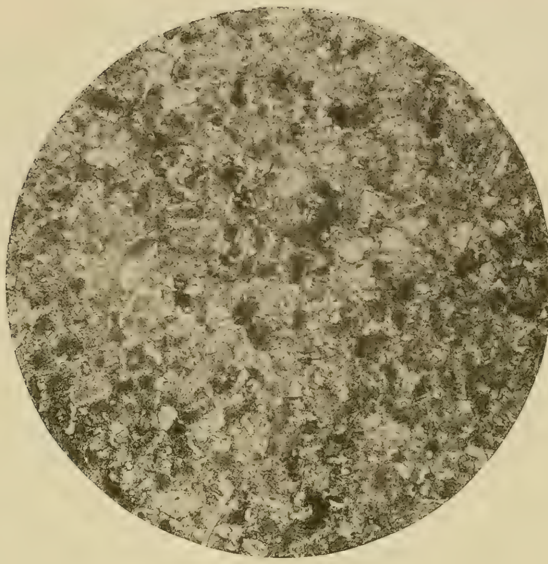
(Sp. No. 32713. Without analyzer, x 35.)

Water-deposited sand. This volcanic sand consists chiefly of feldspar and hornblende. The rounded nature of the feldspar grains is readily seen. Under the microscope some of these show secondary enlargements. The hornblende is in irregular areas, and is presumed to be secondary after fragments of augite. (Described, p. 144.)

Fig. *B*.

(Sp. No. 32711. Without analyzer, x 17.)

Water-deposited volcanic sediment. This illustration shows very clearly the gradation from the medium-grained volcanic sand in the lower portion of the section, through the finer-grained material, to the very fine grained dust. The very fine grained material was deposited following the contours of a large pebble, which is shown in the upper portion of the figure. The fragments of this sand consist chiefly of basalt. There are some which were probably feldspar. (Described, p. 144.)



(*A*)

(*B*)

(*A*) WATER DEPOSITED SAND.

(*B*) GRADATION IN WATER DEPOSITED CLASTIC.

THE MERIDEN GRAVURE CO.

PLATE XXXIV.

PLATE XXXIV.

Fig. *A*.

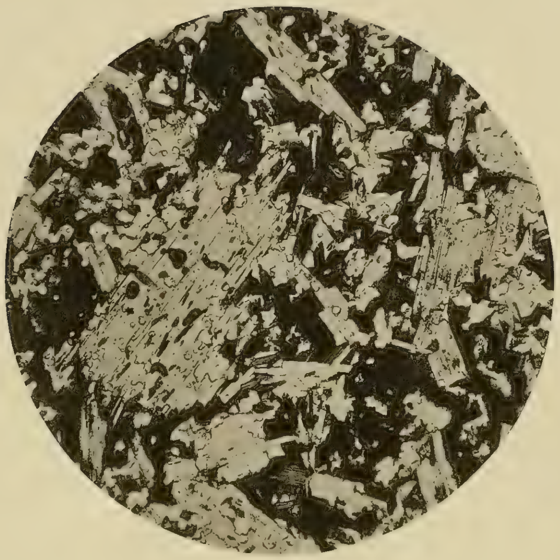
(Sp. No. 23746. Without analyzer, x 17.)

Contact product of a granite. This muscovite-biotite-gneiss (?) is the result of contact action of a granite upon a graywacke. Complete recrystallization of the sedimentary rock has taken place, with the production of a porphyritic schistose structure. The large porphyritic muscovite plates seen as white areas in the photomicrograph evidently represent the last products of recrystallization, as they include all of the minerals which have been previously formed. They are possibly to be looked upon as the product of mineralizers, to whose action may also be referred the presence of tourmaline, which occurs in the section. The irregular white areas represent quartz and feldspar. Dark greenish-brown biotite is included in the muscovite, and with iron oxides occupies the areas which in the figure are dark. (Described, p. 197.)

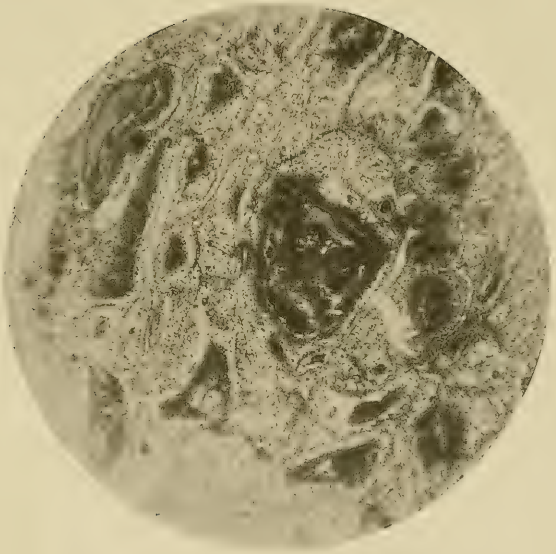
Fig. *B*.

(Sp. No. 23226. Without analyzer, x 17.)

Photomicrograph showing the brecciated character of the matrix which is at times found between the ellipsoids in the ellipsoidal basalts. In this specimen the schistose character is not so marked as it is at times. (Described, p. 117.)



(*A*)



(*B*)

(*A*) CONTACT PRODUCT OF GRANITE.

(*B*) BRECCIATED MATRIX BETWEEN ELLIPSOIDS.

THE MERIDEN GRAVURE CO.

PLATE XXXV.

PLATE XXXV.

FIG. *A*.

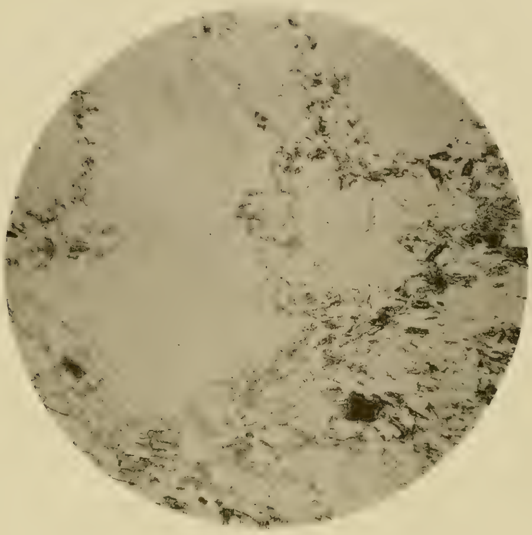
(Sp. No. 26059. Without analyzer, x 18.)

Photomicrograph showing an eruptive contact between granite and metamorphosed sedimentary rock. As a result of this contact the elements of the granite have become partly automorphic. The center of the figure is occupied by a quartz phenocryst which is partly surrounded by the schistose metamorphic product. It contains, near the edge, grains of feldspar and flakes of mica, and thus an imperfect poikilitic zone is produced. The mineral constituents of the metamorphosed sedimentary are arranged parallel to the contours of the phenocrysts. (Described, p. 198.)

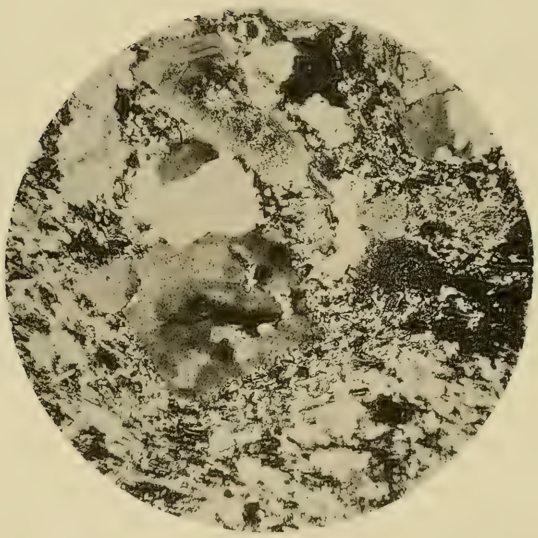
FIG. *B*.

(Sp. No. 26059. With analyzer, x 18.)

The same section as the above, viewed between crossed nicols. (Described, p. 198.)



(*A*)



(*B*)

(*A*) CONTACT OF GRANITE AND SEDIMENTARY.

(*B*) CONTACT OF GRANITE AND SEDIMENTARY SEEN BETWEEN CROSSED NICOLS.

THE MERIDEN GRAVURE CO.

PLATE XXXVI.

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PLATE XXXVI.

FIG. *A*.

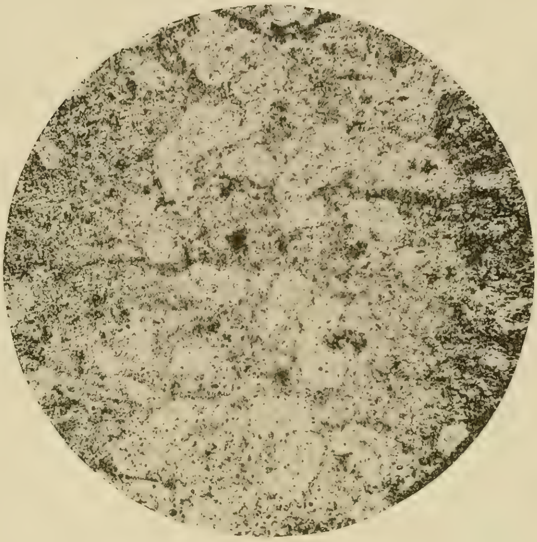
(Sp. No. 32827. Without analyzer, x 38.)

Photomicrograph illustrating a rather exceptional form of spilosite with white spots lying in the fine-grained groundmass. Albite, with a very small amount of chlorite and epidote, forms the spots. (Described, p. 206.)

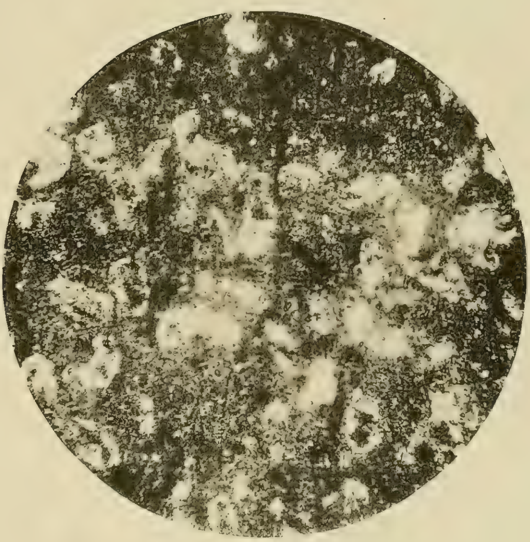
FIG. *B*.

(Sp. No. 32827. With analyzer, x 38.)

This is the same section as above, viewed between crossed nicols, showing the aggregate character of the spots of this spilosite. (Described, p. 206.)



(*A*)



(*B*)

(*A*) SPILOSITE.

(*B*) SPILOSITE SEEN BETWEEN CROSS NICOLS.

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PLATE XXXVII.

303

PLATE XXXVII.

Fig. *A*.

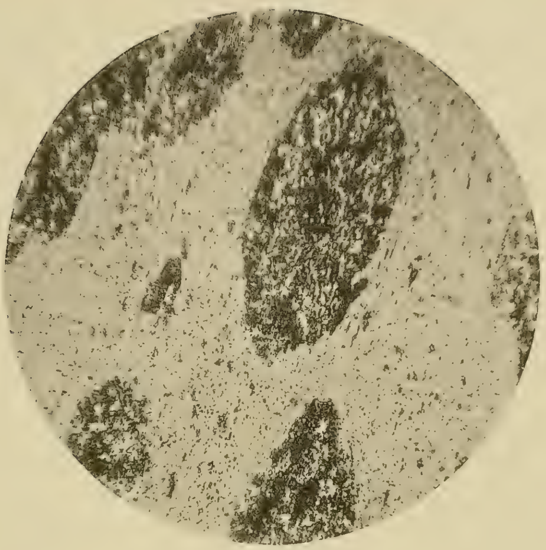
(Sp. No. 32958. Without analyzer, x 18.)

Normal spilosite. Oval spots of macroscopical size, in which chlorite is the predominant constituent, with some quartz, feldspar, rutile, and muscovite, are sharply defined from the surrounding fine-grained groundmass, consisting of the same constituents, but with the muscovite in large quantity and the chlorite very subordinate. (Described, p. 206.)

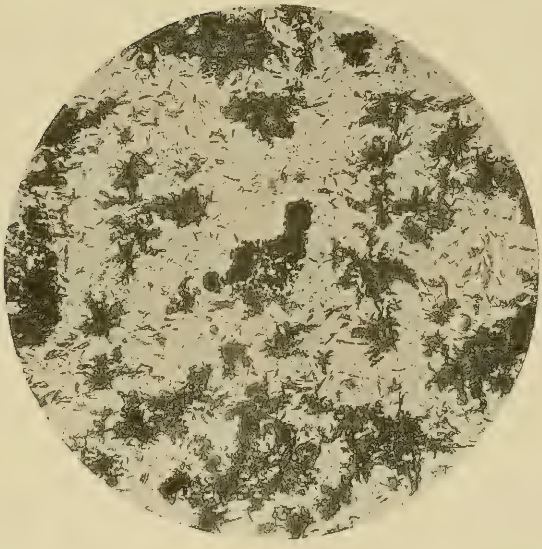
Fig. *B*.

(Sp. No. 32861. Without analyzer, x 38.)

Spilosite in which the spots are of microscopical size and consist predominantly of chlorite aggregates lying in the fine-grained quartz-albite groundmass. (Described, p. 207.)



(*A*)



(*B*)

(*A*) SPILOSITE.

(*B*) SPILOSITE.

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PLATE XXXVIII.

PLATE XXXVIII.

FIG. *A*.

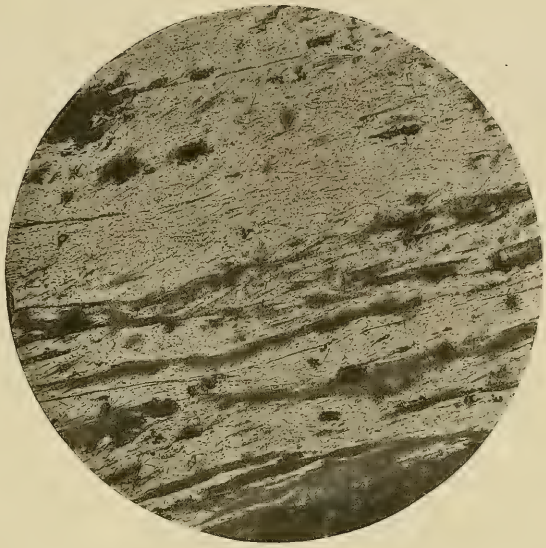
(Sp. No. 32826. Without analyzer, x 38.)

Photomicrograph illustrating the passage of spilosite to a desmosite. In the upper portion, especially in the upper left-hand corner, of the figure, chlorite aggregates similar to those illustrated in fig. *B*, Pl. XXXVII, are seen. These become united, and thus there is a passage into the banded product. This banded character is well shown in the lower half of the photomicrograph. (Described, p. 207.)

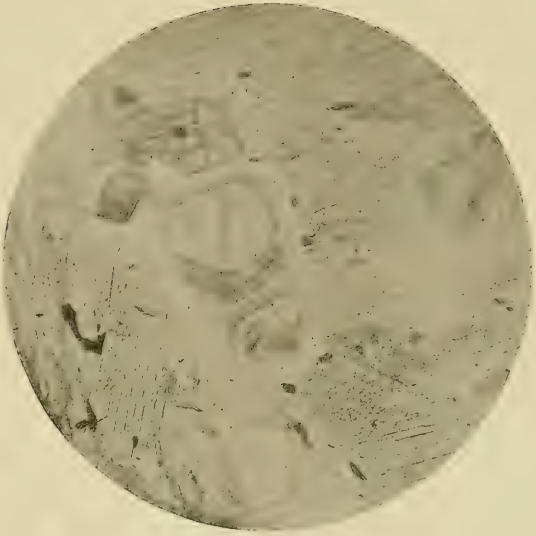
FIG. *B*.

(Sp. No. 23755. Without analyzer, x 90.)

Occurrence and alteration of bronzite in bronzite-norite. This illustration shows the way in which the bronzite occurs in the bronzite-norite. It is frequently included in the hornblende. The bronzite alters around the edges and along the cracks to a yellowish-green fibrous serpentine mineral, which is represented in the section by the dark fibrous material next to the unaltered bronzite. This secondary mineral then alters to a scaly aggregate of talc. These two secondary products can be seen bordering the bronzite, especially well where it is traversed by a crack. (Described, p. 238.)



(*A*)



(*B*)

(*A*) PASSAGE OF SPILOSITE INTO DEMSOSITE.

(*B*) ALTERATION OF BRONZITE IN BRONZITE NORITE.

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PLATE XXXIX.

PLATE XXXIX.

Fig. *A*.

(Sp. No. 23321. With analyzer, x 35.)

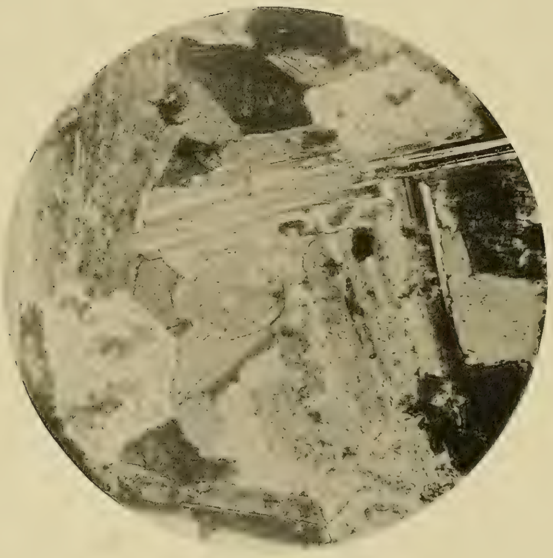
Photomicrograph of a section of biotite-granite from the center of a dike 5 feet wide. On the borders of the dike the magma has crystallized as a normal mica-diorite without quartz and orthoclase. (Described, p. 226.)

Fig. *B*.

(Sp. No. 26023. With analyzer, x 35.)

Mica-diorite showing tendency toward an ophitic texture. Plagioclase is the most automorphic mineral. Biotite is next, but it is poorly developed. Orthoclase and quartz fill irregular areas between the plagioclase. (Described, p. 231.)

(*A*)



(*B*)

(*A*) BIOTITE GRANITE.

(*B*) MICA DIORITE.

PLATE XL.

PLATE XL.

Fig. *A*.

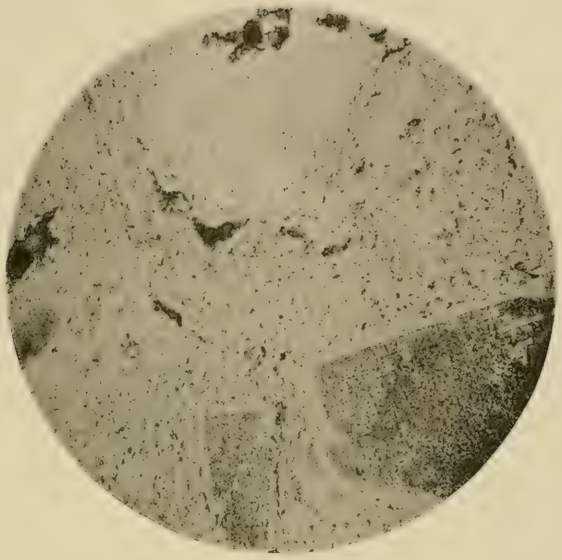
(Sp. No. 32643. Without analyzer, x 35.)

Quartz-mica-diorite-porphyry. The phenocrysts of feldspar and quartz stand out clearly from the fine micrograuitic groundmass. Mica phenocrysts are not seen in this figure, which is intended chiefly to illustrate the character of the feldspar phenocrysts. Muscovite has resulted from their alteration. The zone which surrounds the altered center is very fresh, and is rendered poikilitic by inclusions of minute grains ot quartz. (Described, p. 229.)

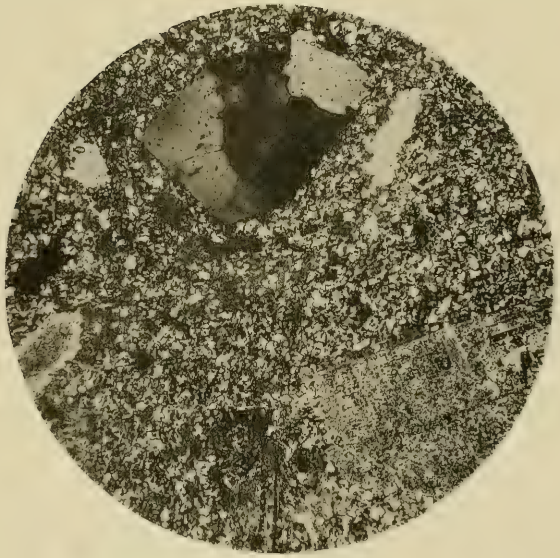
Fig. *B*.

(Sp. No. 32643. With analyzer, x 35.)

Quartz-mica-diorite-porphyry. The same section, viewed between crossed nicols. The micro-granitic texture of the groundmass is well shown. (Described, p. 229.)



(A)



(B)

(A) MICA DIORITE PORPHYRITE.

(B) MICA DIORITE PORPHYRITE SEEN BETWEEN CROSSED NICOLS.

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PLATE XLI.

PLATE XLI.

FIG. *A*.

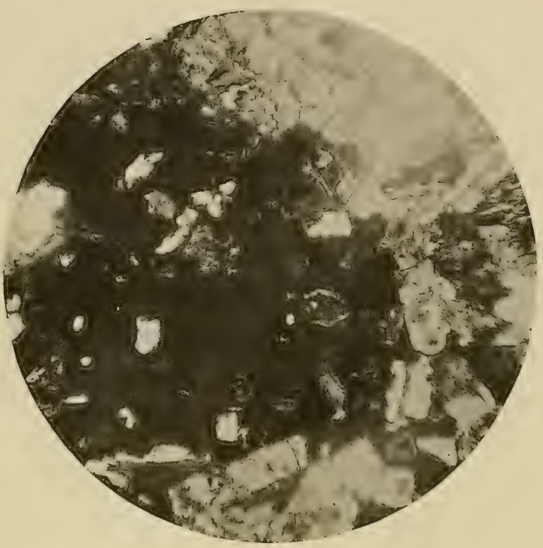
(Sp. No. 23320. Without analyzer, x 18.)

Porphyritic poikilitic hornblende-gabbro. The brown hornblende occupying the center of the phenocryst grades over into a dull-green hornblende. Feldspar and pyroxene are included in the hornblende. (Described, p. 241.)

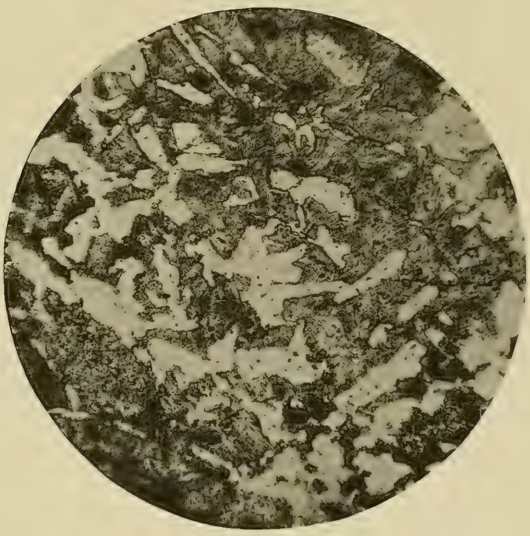
FIG. *B*.

(Sp. No. 23344. With analyzer, x 18.)

Hornblende-gabbro showing a poikilitic texture. The tendency of the feldspars toward a lath-shaped development is very evident. Were they lath-shaped the texture would agree with the Lévy definition of the ophitic texture. (Described, p. 233.)



(*A*)



(*B*)

(*A*) PORPHYRITIC POIKILITIC HORNBLENDE GABBRO.

(*B*) POIKILITIC HORNBLENDE.

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PLATE XLII.

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PLATE XLII.

Fig. *A*.

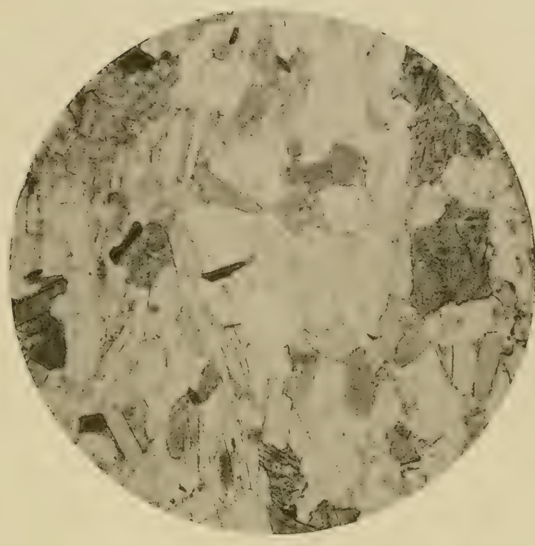
(Sp. No. 23754. Without analyzer, x 38.)

A moderately fine grained hornblende-gabbro showing parallel texture. This hornblende-gabbro occurs in dikes cutting the coarse forms of hornblende-gabbro. The specimen shows very clearly the parallel texture rather commonly found in sections from these dike rocks. This texture is best developed nearest the contact, and is presumed to be a flow texture. The chief mineral constituents—plagioclase, hornblende, and mica—can be readily distinguished in the section. (Described, p. 244.)

Fig. *B*.

(Sp. No. 23754. With analyzer, x 38.)

The parallel texture in the hornblende-gabbro is brought out somewhat better when viewed between crossed nicols. (Described, p. 244.)



(*A*)

(*B*)

(*A*) HORNBLENDE GABBRO.

(*B*) HORNBLENDE GABBRO SEEN BETWEEN CROSSED NICOLS.

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PLATE XLIII.

PLATE XLIII.

Fig. *A.*

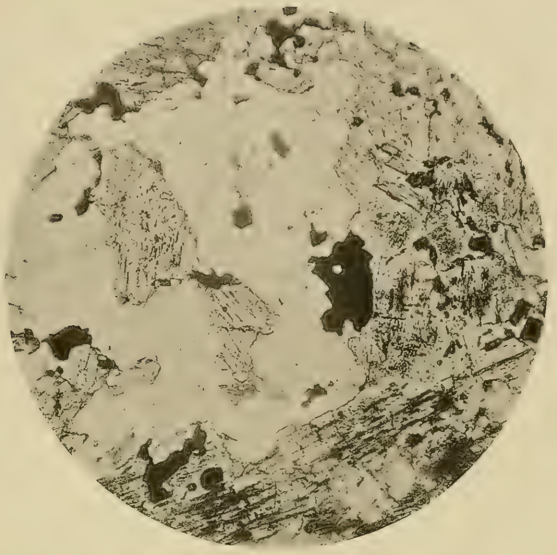
(Sp. No. 26070. Without analyzer, x 17.)

Normal granular hornblende-gabbro. This illustrates the normal medium-grained hornblende-gabbro which occurs in this district. The mineral constituents hornblende, feldspar, and iron oxide can be readily distinguished. (Described, p. 248.)

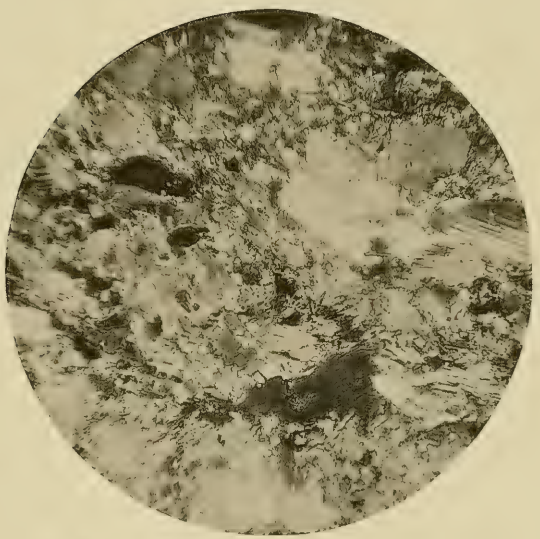
Fig. *B.*

(Sp. No. 26069. With analyzer, x 18.)

Schistose hornblende-gabbro. This illustrates a crushed specimen of a normal hornblende-gabbro such as is represented above in fig. *A.* In this the feldspar has been partly granulated, and new feldspar and quartz has resulted therefrom. The hornblende has also to a considerable extent been recrystallized as light-green secondary hornblende. The mica has become chloritized. These are the important secondary products. A very fair schistose structure has resulted from the crushing. Carried to its full extent, metamorphism of this rock would result in producing an amphibolite or a hornblende-gneiss. (Described, p. 248.)



(*A*)



(*B*)

(*A*) COARSE HORNBLENDE GABBRO.

(*B*) SCHISTOSE HORNBLENDE GABBRO.

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PLATE XLIV.

PLATE XLIV.

Fig. *A*.

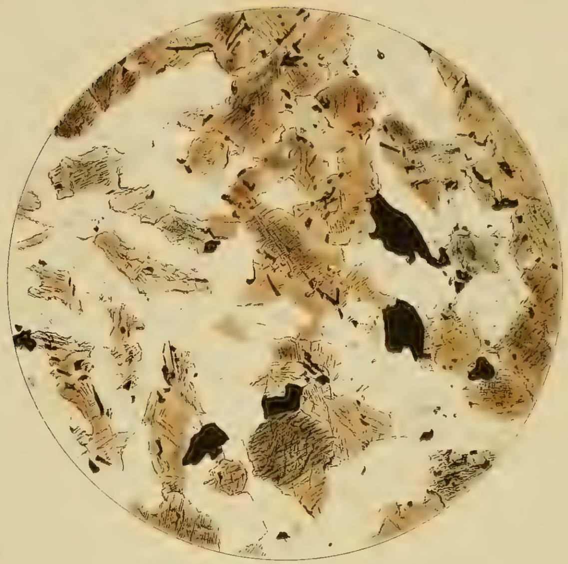
(Sp. No. 23319. Without analyzer, x 35.)

Moderately fine grained hornblende-gabbro. The constituents hornblende, plagioclase, and iron oxide can be readily recognized. Many of the hornblende individuals contain a great number of minute inclusions. (Described, p. 240.)

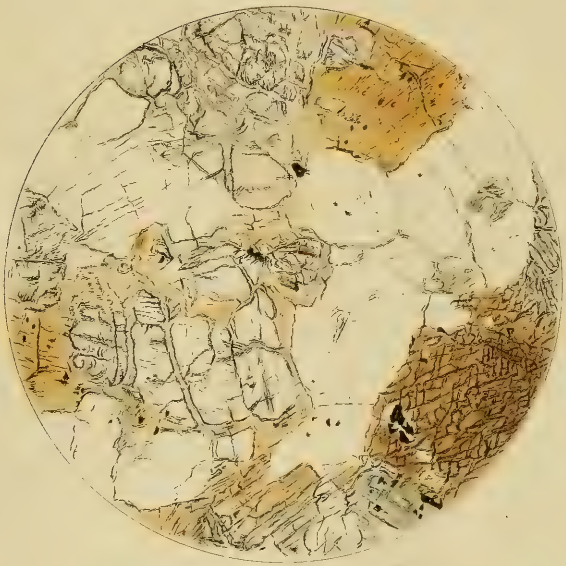
Fig. *B*.

(Sp. No. 23755. Without analyzer, x 35.)

Bronzite-norite. The rock consists of bronzite, hornblende, and plagioclase. The bronzite individuals show a tinge of green and pink, and are slightly fibrous, due to beginning alteration. Cracks, filled with alteration products, cross them. The bronzite is frequently surrounded by a rim of brown hornblende. In some parts of the rock it is partly automorphic. The hornblende can be readily recognized by its strong yellowish and reddish-brown color. It is in anhedra. The plagioclase is the white mineral including numerous minute dark specks. It, like the bronzite, is xenomorphic. (Described, p. 244.)



A.



B.

F. K. Denniston, del.

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A. HORNBLENDE-GABBRO.
B. BRONZITE-NORITE.

PLATE XLV.

PLATE XLV.

Fig. *A*.

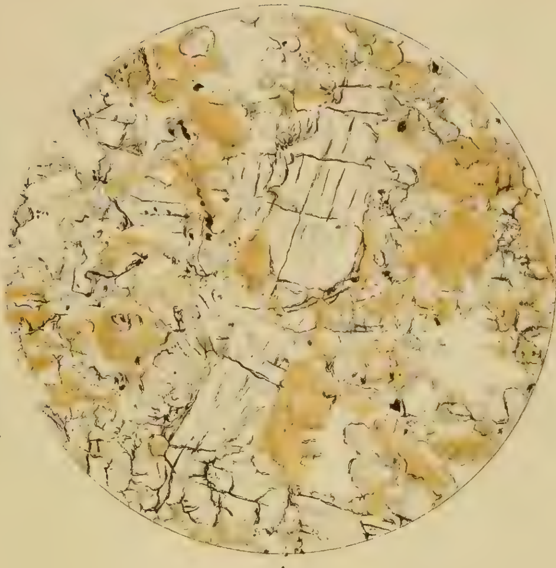
(Sp. No. 23356. Without analyzer, x 35.)

Bronzite-norite-porphyry. The phenocrysts of bronzite lie in a groundmass of bronzite, monoclinic pyroxene, hornblende, and feldspar. In the drawing the bronzite and monoclinic pyroxene of the groundmass can not be distinguished. (Described, p. 247.)

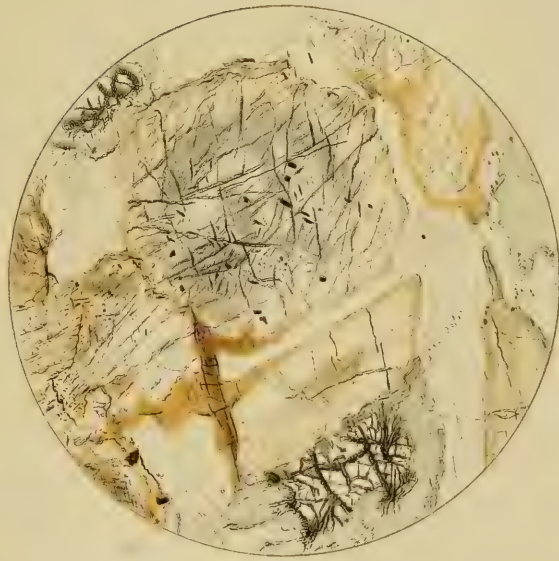
Fig. *B*.

(Sp. No. 23353. Without analyzer, x 18.)

Feldspathic wehrlite. One can readily distinguish the constituents—augite, hornblende, olivine and feldspar—in the illustration. The augite is automorphic where it is near the feldspar. It is surrounded by a brown hornblende zone. Between the olivine and the feldspar there are always two zones. One, the inner one, best seen between crossed nicols, is orthorhombic pyroxene; the other, the outer one, is compact green hornblende. This green hornblende is in optical continuity with the brown hornblende which surrounds the augite. (Described, p. 255.)



A.



B.

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A. BRONZITE-NORITE-PORPHYRY.
B. FELDSPATHIC WEHRLITE.

PLATE XLVI.

PLATE XLVI.

FIG. *A*.

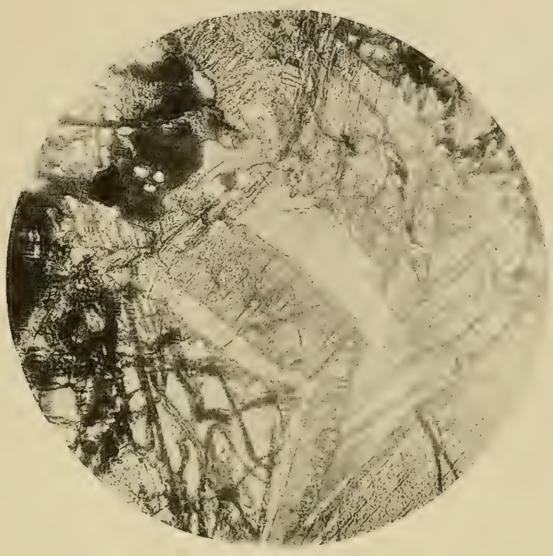
(Sp. No. 23353. With analyzer, x 90.)

Wehrlite. There are shown in this illustration the zones of orthorhombic pyroxene and hornblende which lie between the olivine and feldspar. (Described, p. 255.)

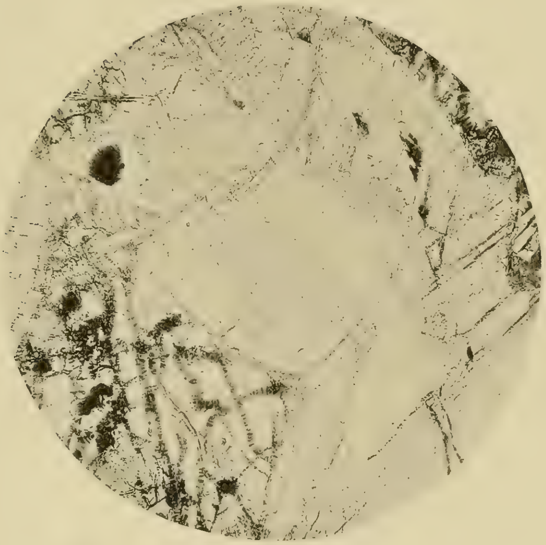
FIG. *B*.

(Sp. No. 23353. Without analyzer, x 90.)

Wehrlite. The ramifying feldspar growths in the hornblende can be seen better when the section is viewed with the analyzer in, as in fig. *A*. (Described, p. 255.)



(*A*)



(*B*)

(*A*) WEHRLITE VIEWED BETWEEN CROSSED NICOLS.

(*B*) WEHRLITE.

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THE CRYSTAL FALLS IRON-BEARING DISTRICT OF MICHIGAN

Part II.—THE EASTERN PART OF THE DISTRICT, INCLUDING THE FELCH MOUNTAIN RANGE

By HENRY LLOYD SMYTH

WITH

A CHAPTER ON THE STURGEON RIVER TONGUE

By WILLIAM SHIRLEY BAYLEY

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ILLUSTRATIONS.

THE CRYSTAL FALLS IRON-BEARING DISTRICT OF MICHIGAN.

PART II. THE EASTERN PART OF THE DISTRICT, INCLUDING THE FELCH MOUNTAIN RANGE.

By Henry Lloyd Smyth.

With a Chapter on the Sturgeon River Tongue, by William Shirley Bayley.

CHAPTER I.

GEOGRAPHICAL LIMITS AND PHYSIOGRAPHY.

INTRODUCTION.

The territory to be described in this and the four following chapters is situated in the Upper Peninsula of Michigan, between the Marquette and Menominee iron ranges, and is all embraced within T. 42 N., Rs. 28–30 W., and Ts. 42–47 N., Rs. 30–31 W. The area of about 300 square miles included within these townships had for the most part been covered hastily by previous reconnaissances of the Lake Superior Division of the United States Geological Survey, the results of which were placed at my disposal. Our task was to go over with especial care those portions in which outcrops had been found by our predecessors, or which seemed likely to contain the iron-bearing formations. At the same time much of the rest was examined more hurriedly.

The tract surveyed in detail comprises a continuous belt about 30 miles in length, and of width varying from 2 to 5 miles, lying wholly within the drainage basin of the Michigamme River and its principal upper tributary, the Fence River, and extending southward from the northern end of the Republic tongue, where it was connected with rocks of well-determined Marquette types, as far as the south line of T. 43 N., R. 31 W. From this line we passed southeast (leaving a gap of 5 miles) across the low

divide between the Michigamme and the headwaters of the Sturgeon, to the Felch Mountain range, which was then carefully studied for a distance extending 13 miles to the east.

Until within the last few years the larger part of this area had been very difficult of access, and much of it is difficult still. The rock surface is almost wholly concealed by a cover of glacial deposits of various kinds; dense forest and great swamps also obscure the rocks, and make traveling difficult and slow. It is therefore not a field to invite geological study. While exploration for iron ore has here and there passed the frontiers of the productive ranges on either side, the general ill-success which attended the early enterprises has discouraged the active search that would at least have resulted in important additions to geological knowledge. For these reasons the area as a whole, with the exception of the Felch Mountain range, has remained almost unknown geologically, until our work in 1892. The references to it in geological literature are consequently but few in number, and are for the most part merely the records of the unrelated observations of casual visitors.

The district, nevertheless, deserves attention from both the economic and the geological standpoint. The iron-bearing formations of the Marquette range extend into it from the north, those of the Menominee range from the south. On the west the ore deposits of the Crystal Falls area are connected geographically at least with the western extension of the Menominee range. Between these boundaries the area stands as the largest one remaining in Michigan in which iron-bearing formations are known to occur, but as yet not yielding important bodies of ore. Here, too, if anywhere, the questions of the equivalence or nonequivalence of the individual formations of the Marquette and Menominee iron-bearing series are to be answered.

It is proper to state that the field study, in consequence of the conditions under which this work was done, was almost wholly directed to economic questions, and that it was not originally anticipated that the results were to be published as a monograph on the district. This will explain the very brief space devoted to the Archean in the following pages. The field work was begun and ended in 1892. Since that time there has been no opportunity to revisit localities, and the conclusions now stand essentially as they were reached in the field. Considering both the obscurity and com-

plexity of the area, it is very probable that further study of important localities would clear away many of the difficulties, as well as modify certain of the opinions now held.

The writer was efficiently aided in the field work by Messrs. Samuel Sanford and Charles N. Fairchild for nearly the whole period, and E. B. Mathews and H. F. Phillips for part of it, as assistant geologists, and by Messrs. Lewis and Forbes as skilled woodsmen.

PRELIMINARY SKETCH OF THE GEOLOGY.

The rocks of the Michigamme and Felch Mountain areas range in age from Archean to early Paleozoic. North and west of the Michigamme River, where geological boundaries are most susceptible of determination, the granites and gneisses of the Archean come to the surface in three oval areas of great regularity of outline, from 10 to 12 miles long by 2 to 6 miles wide, while the intervals between the Archean ovals are occupied by highly tilted sedimentary and igneous rocks of Algonkian age. The lower member of the Algonkian has derived its materials from the wasting of rocks lithologically similar to the underlying granites and gneisses. In the southern and eastern portions of the district the edges of the tilted older rocks are partially covered by a blanket of gently dipping sandstones of Cambrian age, very soft and easily disintegrating. These rocks first appear near the Michigamme River as detached outliers. In going south and east from that river the separated patches become larger and more abundant, until finally a few miles beyond the eastern limit of our work in the Felch Mountain range they unite and entirely cover the pre-Cambrian formations.

CHARACTER OF THE SURFACE.

In its most general aspect the surface throughout this area is a plain, somewhat rolling indeed, which slopes gently upward from the southeast toward the northwest. The surface is formed partly by the soft and gently inclined Upper Cambrian sandstones and partly by the much harder and highly tilted pre-Cambrian rocks of diverse physical and mineralogical characters, and yet over all it maintains a very uniform slope. On the southeast, in the Felch Mountain range, the plain has an average elevation above the sea of 1,200 to 1,300 feet. In the northwest, in the southern

sections of T. 47 N., R. 31 W., the average elevation is 1,800 to 1,900 feet. Since the intervening distance is somewhat more than 30 miles, the general slope is therefore less than 20 feet to the mile.

The minor topographical features based upon this plain are multitudinous in variety and detail, but generally quite insignificant in relief. The maximum difference of elevation between the top of the highest hill and the bottom of the neighboring valley is less than 300 feet, and this is reached in but two cases. The country possesses no commanding eminences, and in the widest panoramas now and then obtainable from the summits of glaciated knobs the background is restricted to a radius of a few miles. In these the general evenness of the sky line is usually broken only by the remnants of the old forest, which have not yet succumbed to fire and the lumberman.

These lesser features have been shaped mainly by the work of the continental ice-sheet, both through the materials which it brought in and through those which it carried away. In the areas underlain by relatively massive rocks, particularly the Archean crystallines, the surface has been left mammillated with rocky knobs, which doubtless were the unattacked cores rising into the pre-Glacial zone of disintegration. These are separated by the similar inverse forms, now for the most part occupied by swamps. In the Archean borders of the Felch Mountain area, where the glacial cover was originally thin, the periodical fires that have followed lumbering operations have burned out the organic matter from the soil and so loosened it that, on the steeper slopes, it has been entirely washed away and the rock surface laid bare. The hummocks and bowls are generally elongated east and west, which is the direction both of the gneissic foliation and of the ice movement. The elevations rise, often with steep, smooth walls, for 5, 10, 20, or even in some cases 60 feet, above the intervening depressions. The latter hold muskeg to the rims. In the wet season they fill with water, which overflows to the next bowl below, but permanent lines of minor drainage, here as elsewhere in the Archean areas, are very infrequent.

Over most of the area, however, the ice has spread a sheet of till, and has here and there deposited the materials swept along in the subglacial streams in characteristic complexity of form and grouping. The more prominent elevations are, in fact, deposits of modified drift, although occasionally

small rock masses like Michigamme Mountain, which is composed of material that offers a most stubborn resistance to all degrading agents, reach an elevation of 100 to 200 feet above the general level of the surrounding country. The fact that the name "mountain" has been applied to hillocks of this order by the surveyors and woodsmen, who have the widest knowledge of the Upper Peninsula, conveys perhaps the clearest idea of the generally level character of the surface.

While the details of the topography are thus mainly glacial in origin, the broader features of the next order of importance have often clearly been determined by the presence of the more resistant rocks. The large structural domes of the Archean, which are such characteristic geological features, are also indicated by a general upward swell of the surface of the areas which they occupy. The topographical transitions at the margins of these swells are frequently abrupt, and sometimes for considerable distances are marked by scarp-like slopes in the granites, caused by the almost vertical contacts with the softer Algonkian formations. Considerable portions of all three of the Archean ovals in the northern part of the district display this slight topographical prominence. Marginal scarps are particularly well shown in the oval west of Republic, in secs. 19 and 30, T. 47 N., R. 30 W., and along the south side of the oval which lies between the Fence and Deer rivers, near their junctions with the Michigamme. The more important bodies of greenstone also are generally expressed by a noticeable degree of elevation. Thus the great intruded sheets folded in with the Lower Marquette series in secs. 24, 25, and 36, T. 47 N., R. 31 W., give rise to long broad ridges that closely follow the changes in the strike. But in all these cases the topographical emphasis is very slight, and the plain as a whole may truly be said to maintain its general slope with practical indifference to the weather-resisting differences in the underlying rocks.

These broader swells of the harder rocks are separated by broad, slightly lower-lying plains, in many of which a valley character is still distinctly recognizable in spite of the fact that they especially have been favored with deposits of modified drift. The present drainage, in its main lines, largely follows these older valleys, although much confusion, which is especially noticeable in the details, has of course resulted from their partial choking by the drift.

DRAINAGE.

Nearly all the surface water of this district finds its way to Lake Michigan through the Michigamme and the Sturgeon rivers, which are independent branches of the Menominee—the largest river flowing into Lake Michigan from the west. A few square miles along the eastern boundary, however, are tributary to the Ford, which flows into Green Bay north of the Menominee. Of these the Michigamme drains by far the largest part of the district. This river heads in Lake Michigamme, which it leaves in sec. 9, T. 47 N., R. 30 W., near the northeast corner of the area shown on the general map (Pl. II), at an elevation above the sea of 1,580 feet. Thence it flows for 8 miles southeast to Republic, in a synclinal valley cut out of the soft schists of the Michigamme formation. This valley, which is nearly a mile wide at the northern end and less than half as wide at the southern, is bordered on both sides by the harder Archean granites, which rise with rather steep slopes to the general level of the plain. Throughout the length of the valley the river flows over glacial drift, but at Republic, where the soft rocks come to an end, it breaks across rocky barriers in a succession of rapids, and continues first nearly due south (leaving the district covered by our map), and then flows southwest over glacial deposits, which completely mask the bed rock for 10 miles. South of the Archean oval, which occupies the western part of T. 44 N., R. 31 W., and the eastern part of T. 44 N., R. 32 W., the limestones and slates of the pre-Cambrian are again exposed, and over these the Michigamme flows in close conformity to the general strike as far as the range line.

In the southern sections of T. 44 N., R. 31 W., the Michigamme receives two tributaries from the north—the Fence River, which comes from the eastern side of the Archean mass just mentioned, and the Deer River, which comes from its western side. The headwaters of the Deer and of the western branch of the Fence flow through the same section (21) in T. 46 N., R. 32 W., north of the Archean oval, but farther south they diverge to an extreme distance of 10 miles, and afterwards converge so that their points of junction with the Michigamme are but 4 miles apart. The area thus inclosed is broadly concentric with the Archean oval. In the case of the Fence, at least, the river is placed within a wide depression coincident with the softer stratified rocks of the Algonkian, and follows very faithfully their

general strike. Deposits of glacial sand and gravels are very abundant within this valley, and for these the river often swings aside across the strike for a mile or more. In secs. 21 and 29, T. 45 N., R. 31 W., and in sec. 10, T. 44 N., R. 31 W., excellent rock sections are afforded by such digressions.

The old valley between the two Archean ovals west of the Republic tongue (see Pl. III) is on the south entirely filled with glacial gravels to the level of the old divides, and the large brook known as the east branch of the Fence is diverted to the till-covered western of the two Archean ovals. The valley is clearly indicated, however, by an interesting series of lakes, of which Squaw, Trout, and Sundog, each about 1 mile in length, are the most considerable.

The area drained by the Sturgeon lies in the extreme southeastern part of the district, wholly within the marginal fringe of sandstone. The relation of its course to the geology is known in detail only within portions of the Felch Mountain range. This it first enters in the northern portions of secs. 35 and 36, T. 42 N., R. 30 W., in a loop into the Algonkian, from the northern Archean margin, to which it again returns. Five miles farther east it crosses the trough from north to south, transverse to the strike of the Algonkian formations, to the contact with the southern Archean mass. It follows this contact eastward for 2 miles, and then strikes southward across the Archean to the Menominee River, not again returning to the Felch Mountain range. The river valley in the Felch Mountain range is very distinct, and where bordered by Potsdam outliers is rather deep, with precipitous banks. It is but slightly affected by drift deposits. Its course shows an almost complete disregard of the structure of the Algonkian and Archean rocks, and so has the usual characters of a superimposed stream.

The Michigamme River, as was early noted by Pumpelly, has practically no eastern branches within this district. The Escanaba and Ford rivers, which reach Lake Michigan directly, and the Sturgeon, which joins the Menominee below the mouth of the Michigamme, all head within 2 or 3 miles of the latter, the course of which is transverse to their general direction. The Michigamme thus flows along the eastern edge of its drainage basin. This fact—the most striking in the general distribution of the streams of the district—is the result of causes which, in part at least, go back to very remote geological periods.

CHAPTER II.[1]

MAGNETIC OBSERVATIONS IN GEOLOGICAL MAPPING.

SECTION I. INTRODUCTION.

As has been said already, the area in which our work was done is largely drift covered, to somewhat varying but usually considerable depths; the mantle on the whole is so evenly spread that outcrops of any rocks except those belonging to the Archean are in many sections few and scattered and sometimes are almost entirely lacking over whole townships.

Under these circumstances, and since also the pre-Cambrian rock structure is complex, even a general outlining of the old formations would be impossible by the usual geological methods, and if we were restricted to these there would be no alternative but to map most of the territory as Pleistocene. It happens, however, that the Algonkian rocks of Michigan contain a large amount of magnetite, which is known from observation in the developed ranges to be characteristic of certain geological formations. It undoubtedly occurs in more or less amount in all the sedimentary rocks and is also present, sometimes in considerable quantities, in rocks that are not sedimentary, as, for example, around the margins of the old intrusive diorite bosses. But generally speaking, its occurrence in large quantities is confined so closely to definite geological formations, in which it is found in characteristic association with certain other minerals, or to horizons within those formations, that it can be guardedly used in identifying them, and in tracing them from localities where they outcrop through areas in which they are buried. This use is not only justified, from an empirical standpoint, by the presumption in favor of analogies to which no exceptions are known, but it has a rational basis, in the view of the late Professor Irving,[2] which is

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[1] This chapter is abridged from a paper of the same title presented at the Colorado meeting of the American Institute of Mining Engineers in September, 1896.

[2] Classificatior of early Cambrian and pre-Cambrian formations, by R. D. Irving: Seventh Ann. Rept. U. S. Geol. Survey, 1888, pp. 451–452.

steadily gaining ground, that at least much of the iron of this magnetite was originally buried in the same formations in which it now occurs, through the agency of organic life. From this point of view the magnetite is in a certain sense a fossil, but with the important practical advantage over other organic remains, that it need not be dug up in order to prove its existence.

These magnetite-bearing rocks always produce disturbances in the compass-needles held in their neighborhood. By a systematic location and comparison of these disturbances the position of the rocks which produce them can be determined with a considerable degree of precision, even when they are deeply buried. Besides their position on the map, the magnetic observations may, and often do, indicate certain other geologically important facts, such as whether the rocks are flat lying or highly tilted, the direction of strike and dip, and, in some cases, the depth to which they are buried. The methods employed in the field work were based on those described by Maj. T. B. Brooks,[1] who perfected the dial compass and predicted the importance of magnetic methods in geological mapping; but the results reached in interpretation were gradually developed in the progress of this work, as we were daily brought face to face with phenomena which called for explanation.

It must be clearly understood at the outset that in the iron ranges of the south shore of Lake Superior magnetite is rarely concentrated in large bodies, and that, in fact, its known occurrence as such is restricted to a small part of the western Marquette district, where in one producing mine it now forms practically the whole product and in another a variable but usually important part of the whole. It is therefore well understood in the Upper Peninsula that disturbances of the magnetic needle, however great, do not mean workable deposits of magnetite. Whatever significance such disturbances possess is stratigraphical, and properly interpreted may lead to discoveries of rich ore, other than magnetite, in formations to the position and attitude of which the attractions may furnish a clew. But it may be asserted as a general proposition, the essential truth of which has been established by the experience of many years, that in the region referred to magnetic disturbances usually mean that magnetic iron ore in a workable deposit does not exist in the area of disturbance.

[1] Geological Survey of Michigan, Vol. I, Part I, 1873, Chapter VII.

SECTION II. DESCRIPTION OF THE MAGNETIC ROCKS.

The magnetic rock of the Lower Huronian series of the western portion of the Marquette area, which is of special importance to notice, since it forms one of the chief horizons of reference to which our work is tied, is the Negaunee iron formation. It is finely exposed at the south end of the Republic trough; but farther north has been greatly reduced in thickness, or locally cut out altogether,[1] by the Upper Marquette denudation, and, where present at all, is usually drift covered.

This rock often possesses a very distinct banding, caused by the alternation of layers, in which one of the constituent minerals predominates over the others, sometimes, indeed, to their total exclusion. In the lower part of the formation, quartz and grünerite constitute the bulk of the rock, with magnetite scattered somewhat indiscriminately through them. Higher up, the magnetite and quartz relatively increase, until near the top, but below the jasper, the grünerite goes out almost entirely, and the rock consists of quartz bands, heavily charged with magnetite, in alternation with bands of nearly pure magnetite. In the Negaunee formation, as exposed at Republic, the magnetite therefore occurs concentrated in some of the parallel bands and disseminated through the others.

In the same district there is another much less prominent locus of magnetite at and near the base of the Upper Marquette or "hanging-wall" quartzite. Along the strike of this zone, which is of small thickness, the distribution of magnetite is very irregular; and for this and the additional reason that when the magnetic portion of the Negaunee formation comes up to it the disturbances which it produces can not be discriminated from those produced by the latter, the position of the plane usually can not be inferred.

In the Menominee district and its extensions there are two horizons in the lower series, characterized by the presence of magnetite. The lower of these is not known to outcrop, but it occurs somewhere near the junction of the dolomite and the underlying quartzite. The magnetic disturbances due to this formation are feeble, but they are quite persistent in the Felch Mountain area, and have thrown some light on the geological structure.

[1] The Marquette iron-bearing district of Michigan, by C. R. Van Hise and W. S. Bayley, with a chapter on the Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey, No. XXVIII, 1897, pp. 531, 537.

The other formation which produces disturbances is that which I have correlated with the Negaunee formation and named in a former paper[1] the Michigamme jasper, but which is here renamed the Groveland formation. This rock, while varying a great deal in character, is generally much like that magnetic phase of the Negaunee formation in which the grünerite is rare or absent. From the fact that it now survives for the most part only in shallow and shattered synclines, it often lacks the regular banding; and hematite is always present in greater or less amount. The relative proportions of the two iron minerals vary along the strike also. The rock as a whole, however, is very magnetic, but not so strongly so as the Negaunee formation in the Republic trough.

In the Felch Mountain range there is still a third magnetic formation, which seems to overlie unconformably the lower series, and is therefore provisionally assigned to the Upper Huronian. This formation consists of ferruginous schists, interstratified with layers of ferruginous fragmental quartzite. It is generally much less highly inclined than the magnetic rocks of the lower series as well as less rich in iron, and the disturbances produced by it are correspondingly small.

Besides these rocks of sedimentary origin, with which this paper properly deals, it may be mentioned that along the Fence River there is a considerable area of metamorphic eruptives, which are often exceedingly magnetic. These are restricted to a definite geological horizon, within which the magnetic disturbances are remarkable for their complexity and irregularity, no doubt as the result of a very irregular distribution of magnetite and of the formations which chiefly contain it. The rocks in portions of this belt outcrop freely, and the disturbances can therefore easily be assigned to the proper causes.

SECTION III. THE DISTRIBUTION OF MAGNETISM IN THE MAGNETIC ROCKS.

Magnetite occurs, therefore, in these Algonkian rocks in different ways. In some instances it is mainly concentrated in nearly pure parallel layers; in others, it is more or less evenly disseminated through non-magnetic material; and still again it is present in both forms. Moreover,

[1] Relations of the Lower Menominee and Lower Marquette series of Michigan (Preliminary), by H. L. Smyth: Am. Jour. Sci., Vol. XLVII, 1894, pp. 217, 218, 223.

these rocks have all been folded, more or less strongly, at more than one period; and wherever they are exposed, they are seen to be inclined to the horizon, often at high angles, and to be traversed by intersecting sets of joint-planes and cleavage-planes, some of which always cut the bedding, and often have been the seat of the development of secondary minerals. By the crossing of these various surfaces, the rocks are divided into small unit masses, at the boundaries of which there is either an actual physical parting or a break in the continuity of the magnetite.

It is well known that when a bar magnet is broken and the severed ends are again joined, the two pieces do not unite to form one magnet, but remain as two. It may be conceived, therefore, from the manner of distribution of the magnetite, and the secondary partings existing in these rocks, that their magnetism is seated in an enormous number of small separate magnets, at least one for each of the physically distinct unit volumes.

It is a fact of observation, as will appear hereafter, that the upper surfaces of these magnetic rocks invariably attract the north end of the compass needles and, of course, repel the south end. From this it must be inferred that the small magnets are generally similarly oriented, and have their north ends, which would repel the north end of the compass needle, pointing downward, and their south ends, which attract it, pointing upward. As this is the arrangement that would result from induction from the earth's magnetism, it can be concluded further (as, of course, might be assumed) that these rocks are magnetic from the earth's induction.

It is also well known that when several bar magnets are joined in line at opposite poles, the effect upon a compass needle within the range of influence is nearly the same as if the joined magnets were replaced by a single magnet of the combined length. For each member of the pairs of intermediate poles, one attracting and the other repelling, is about the same distance away, and their effects so balance each other. The result, therefore, is to leave one pole unchanged in position and to remove the other to the end of the last magnet added. If enough magnets are added, the final result is to carry the moving pole so far away that it has no appreciable influence upon the needle. This is a condition which, from the distribution of the magnetite and the parting surfaces which run through the magnetic rocks, must always be realized more or less completely. It is a necessary consequence of such an arrangement of the small magnets that, in the case

of a thin sheet of magnetic rock lying at a low angle of dip, the buried north poles would not be much farther removed than the upper south poles, and consequently the compass needle should be relatively only slightly disturbed. This is precisely what is found to be the case.

Thus there is firm ground for the conception of the magnetic rocks as made up of sheaves of small magnets, all similarly oriented in a general way and all having their south poles upward at or near the rock surface, while the effective north poles, by the continual addition of similarly oriented sheaves below, are carried down, when the rocks are vertical or nearly so, to such depths that their influence is greatly diminished or altogether imperceptible. In equal small areas the individual magnets are no doubt of very unequal number or strength. This can be proved by holding a swinging needle close to the surface of a magnetic rock, shifting its position without moving it out of the parallel plane and observing the changes in the pointing. These are almost always large and are undoubtedly due to the variations in strength of small areas of the upper poles. In consequence of the law of magnetism, by which the attraction (or repulsion) varies inversely as the square of the distance, the areas immediately surrounding the needle are very much more important factors in the resultant than those farther removed. When the needle is held higher up, or, what is the same thing, the magnetic rock is buried, the effects are much more regular, since a larger number of the unit areas enter into the resultant with equal weight due to equal distance, and the extremes of individual variation are lost in the general mean. Since successive magnetic cross sections over buried rocks show on the whole a great degree of regularity, we can finally conclude that the magnetic force of these rocks is seated in an immense, practically an infinite, number of small magnets, which furnish free magnetism at the upper and lower bounding surfaces of the magnetic formation, and that on the average there is about the same number, of about the same aggregate strength, or, in other words, equal intensity in equal areas of these surfaces, if the areas are taken large enough.

SECTION IV. THE INSTRUMENTS AND METHODS OF WORK.

The instruments used in this work are simple and well known. The dial compass is an ordinary compass, carrying a $2\frac{1}{2}$-inch needle swinging inside a circle graduated to degrees, which is further supplied with a grad-

uated hour circle. It is therefore a portable sundial. The gnomon is a thread, which is attached at one end to the center of graduation of the hour circle near the rear sight and at the other to a point in the forward sight so taken that the angle made by the thread with the plane of the hour circle is equal to the latitude of the place. When this instrument is leveled and set up in the meridian on a sunny day, the thread will cast a shadow on the hour circle at the correct apparent solar time, from which mean time may be determined by applying the equation of time. Conversely, if it is so set up that the shadow of the thread falls on the correct apparent time, the sights of the instrument are in the true meridian. In this position the declination of the horizontal needle may be read off from the graduated circle. At work, this instrument is mounted on a light Jacob's staff, or it may be held in the hand. The Jacob's staff, although often inconvenient to carry, is preferable, as with it the readings are all taken at the same height above the ground and the leveling is more exact and steady. In a correctly constructed instrument, with good time, the readings may be made to half a degree. Correctness in the time, however, is indispensable to good work, and this is best secured by keeping a standard watch in camp and referring the working watches to it daily.

The dip needle needs no description. In geological work that form known as the Norwegian, in which the needle is pivoted on a universal joint, is not so useful as the type in which the needle is rigidly confined to one plane. In taking the readings, this plane in which the needle is free to swing is made to coincide with the vertical plane determined by the pointing of the horizontal needle. The circle is graduated to single degrees, and with skillful work the readings are reliable to one or two degrees. It may be added that the south end is weighted, in order, either partly or completely, to balance the vertical component of the earth's force. It was found better not to balance it completely, but only to such an extent that the north end of the needle would dip about 10° (the graduation zero being horizontal) in an area removed from local disturbances. It is no doubt desirable that all the dip needles used in the same work should be brought to approximately the same index error, in order that the readings may be more directly comparable. In practice, however, it was found quite impossible to keep our three needles in unison, on account of the rough usage to which they were unavoidably subjected. As, however, the form

of the dip curves is really the subject sought, and since these, in the presence of considerable disturbances, are sensibly independent of small differences in the index error, it is not indispensable that the needles should be exactly together.

These instruments are simple, and, of course, do not give precise results. But the observations are rapidly and cheaply made, and to a sufficient degree of accuracy for the end in view. It may be stated again that the object is to detect and compare relative magnetic disturbances, and to find out the bearing of these disturbances on the distribution and attitude of the rocks which produce them. For this purpose the instruments are exceedingly well adapted.

The field work was carried out by parties of two men each, one of whom, a skilled woodsman, carried along the line and observed the horizontal needle, while the other read the dip needle, kept the notes, and attended to the geology. According to the general plan of the field work, a series of parallel lines was run either north and south or east and west across each section. The direction of the lines of travel was chosen so as to cut the strike of the rocks at the largest angle. The probable direction of strike for each day's work could be inferred in advance from what had gone before. If it were more nearly north and south than east and west, the traverse lines were run east and west, and vice versa. These directions were in many cases not the most desirable for the magnetic work alone, but the choice was practically limited by the lines of the United States Land Survey, which give for each square mile eight points of departure (at the four corners and four quarter posts of each section), which are generally identifiable on the ground. On these lines of travel the instruments were read at various intervals, from 5 to 10 or 100 paces, depending upon the local complications. The intervals between the lines varied from one-sixteenth to one-fourth of a mile, and were determined not only by the magnetic complications, but by the character of the surface, it being especially desirable that the ground should be so closely covered that no outcrop could escape detection. The distances along and off the lines of travel were measured by pacing. The general accuracy of the pacing is remarkable, and is essentially within the platting error of the scale of the maps. The average closing error for August, 1892, during which about 100 miles of traverse lines were run, was 20 paces per mile, or 1 per cent.

Two-thirds of the errors averaged 10 paces per mile, or 1 in 200, while the maximum was 1 in 30. But this was better than the average for the season.

The observations at each station consisted in a reading of the horizontal and dip needles. When there was no local magnetic disturbance, the horizontal needle would come to rest in the magnetic meridian, which in this region is about N. 2° to 3° E., or almost coinciding with the true meridian. The dip needle, when held in the same meridian, would indicate the index error. When, however, disturbing material was present, the horizontal needle would point to the east or west of the magnetic meridian, at an angle determined by the direction of the resultant of the horizontal components of the earth's and the local forces. The dip needle would come to rest in the same vertical plane, at an angle with the horizon determined by the amount and direction of the three forces, the whole pull of the earth's force, the whole pull of the local forces, and the balancing weight, and in general would show a downward deflection. After making and recording the set of observations at a station, the party proceeded to the next, and so on to the end of the day. At the end of each day, or as soon as possible afterwards, the day's work was platted on a large-scale map, on which the readings of the horizontal needle were represented by short arrows drawn through the stations, turned east or west of the true meridian, as the case might be, and carrying the amount of declination written at the arrow point. The dip observations were laid off to scale immediately below the stations, measuring all from the same horizontal line, and the points thus established were connected by a free-hand curve.

SECTION V. FACTS OF OBSERVATION AND GENERAL PRINCIPLES.

1. OBSERVED DEFLECTIONS WHEN THE STRIKE IS NORTH AND SOUTH AND THE DIP VERTICAL.

If a magnetic rock, striking north and south and dipping vertically, is crossed by an east-and-west traverse, it is found, as the disturbing belt is approached, say from the western side, that the horizontal needle points toward the east of north, and that this easterly pointing gradually increases to a maximum. Continuing east from the maximum point the eastward declination decreases, and soon a station is reached at which the needle points due north. Still farther east the declination changes to westward, and soon thereafter reaches a westward maximum, beyond which

again the westward pointing in its turn gradually decreases, until finally the needle reaches its normal eastward declination, after passing through a second zero. The dip-needle readings at the same stations generally increase slowly at first, and then rapidly, and soon reach a maximum at the first zero point between the converging arrows; beyond this to the east they decrease correspondingly, so that the dip curve is symmetrical east and west of the maximum These statements will be made clear by a reference to fig. 15, which represents an actual traverse in T. 45 N., R. 31 W.

2. DEFLECTIONS OF THE HORIZONTAL NEEDLE.

It is evident that in crossing a rock belt which stretches away indefinitely in both directions, only a limited part of it will affect the readings on

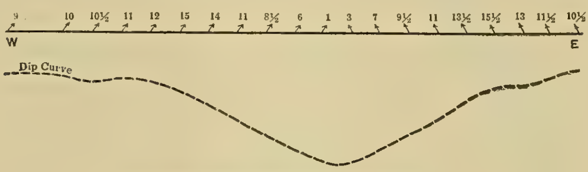


Fig. 15.—Magnetic cross section in T. 45 N., R. 31 W.

a given cross section. Since the pull of the poles of a magnet on a compass needle diminishes with the square of the distance of separation, it follows that the limits to the material that would noticeably disturb comparatively insensitive instruments would soon be reached. If we consider for the moment only the horizontal components, and call the distance a (fig. 16) at which the needle would respond to the attraction of material possessing the magnetic force of that with which we are dealing, then at any station, P, the material inside a circle drawn with P as a center and radius a (shaded in the figure) would exert force on P, the material outside would not. If the circle drawn from a station, P′, does not reach to the magnetic belt, the needles at P′ will not be disturbed.[1]

For reasons of symmetry, it is seen that the attraction of the magnetic

[1] The actual distances at which disturbances of the needles can be detected are exceedingly variable, since they depend (as will be shown hereafter) not only upon the lithological character of the magnetic formation, but also upon its strike, dip, thickness, extent, and nearness to the surface. One formation in which all the conditions are exceptionally favorable distinctly deflects the dial-compass needle at a distance of 3½ miles.

belt would act along the line P N, drawn through P perpendicular to the strike of the rock. Since there is as much material on one side of this line as on the other, the components perpendicular to it will balance each other, and the instruments at P will be affected exactly as if all the attracting material were concentrated along this line. The horizontal needle will take a position in the line of the resultant of the two forces which act upon it, namely, the horizontal component of the earth's magnetism (which acts in the line of the magnetic meridian) and the horizontal component of the material within the circle of attraction (which acts along the line P N). The force which deflects the needle from its general local direction is the component along P N, and it is evident that the greater this component the greater will be the deflection of the needle, since the direction in which it acts always remains the same at all stations for any given direction of strike of the rock. For if β is the strike of the rock measured from the north, and H and H′ are the horizontal components of the earth's and the rock force respectively, it is readily shown that δ, the angle of deflection of the horizontal needle at any station, P, is given by the equation:

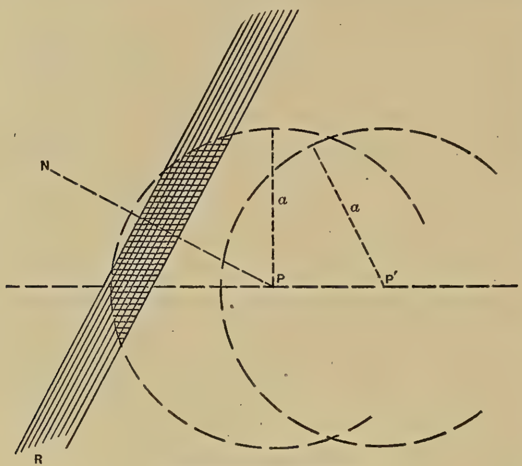


Fig. 16.—Circles of attraction.

$$tan\ \delta = \frac{cos\ \beta}{\frac{H}{H'} \pm sin\ \beta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

From this equation it is easily seen that, no matter how great may be the horizontal component of the force of the magnetic rock, the horizontal needle can not be deflected past the normal.

As P moves toward the magnetic belt the horizontal component at first increases, and with it the westward deflection of the needle. Finally, the maximum westward deflection is reached, beyond which the needle begins to return; it is evident, therefore, that at this point the horizontal component has reached a maximum value.

3. DEFLECTIONS OF THE DIP NEEDLE.

The balanced dip needle (i. e., without index error), in an area of no local disturbance, is in equilibrium under the action of two couples, namely, the vertical component of the earth's magnetism and the added weight. When displaced from the position of equilibrium, the horizontal couple restores it.

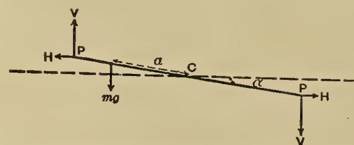


Fig. 17.—The forces acting on the dip needle.

In fig. 17 let PP be a balanced dip needle which has been displaced through the angle α. At the two poles the attraction and repulsion of the earth's magnetism may be resolved into horizontal and vertical components, H and V.

Taking moments about C, we have, if $\alpha=0$, the needle in equilibrium under the couples,

$$V \,.\, 2b - mg \,.\, a = 0,$$

where $2b=$ PP, $mg=$ the added weight, and a its distance from the center.

If this needle, so balanced, is carried to a station within the influence of a magnetic rock, its dip will be determined by the composition of the new forces with the old. The vertical plane will be that in which the horizontal needle points at the same station. The equations above give us a ready means of determining the angle of dip in terms of all the forces.

Suppose the needle finally comes to rest at the angle α with the horizontal (the north pole being depressed). Then

$$V_r \,.\, 2b \,.\, \cos\alpha - mga \cos\alpha - H_r \,.\, 2b \,.\, \sin\alpha = 0, \quad . \quad . \quad . \quad . \quad (2)$$

where H_r and V_r signify the resultants of the horizontal and vertical components of the earth's and the local force.

Equation (2) is easily reduced to

$$\tan a = \frac{2b \,.\, V_r - mga,}{2b \,.\, H_r}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If, however, the dip needle is not balanced, but has, where there is no local disturbance, a constant index error θ (measured from the horizontal), it is readily seen that

$$\tan \theta = \frac{2b \,.\, V - mga}{2b \,.\, H}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In an area of local disturbance the angle of dip α is given by equation (3). Since V and V′ always act in the same line,

$$V_r = V \pm V'.$$

Substituting this and the value of mga from equation (4), equation (3) becomes

$$\tan \alpha = \frac{\pm V' + H \tan \theta,}{H_r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

If the index error is θ', and the corresponding deflection α', we have

$$\frac{\tan \alpha}{\tan \alpha'} = \frac{\pm V' + H \tan \theta}{\pm V' + H \tan \Theta'}$$

Therefore at the same station, the greater the index error the greater is the angle of dip in the same or two similar instruments. It is also evident that the greater the vertical component of the pull of the rock, the less will be the difference between the deflections in the two cases.

From an inspection of equation (5) it is seen that $\tan \alpha = \infty$, or $\alpha = 90°$ only when $H_r = 0$. H_r is, in general, given by the equation

$$H_r = \sqrt{H^2 + H'^2 \pm 2\ H\ H'\ \sin \beta},$$

where β is the strike of the rock measured from the north. H_r can therefore equal zero only when $\beta = \frac{\pi}{2}$, or the rock strikes east and west, and at the same time H′ is numerically equal to H, and acting in the opposite direction. Dips of 90° can not occur in other cases, no matter how strong

the magnetic force of the rock may be. It is also evident that in general H_r has its minimum value when $H' = -H \sin \beta$. When the rock strikes north and south or $\beta = 0$, H_r is a minimum when $H' = 0$.

4. HORIZONTAL AND VERTICAL COMPONENTS WHEN THE MAGNETIC ROCK DIPS VERTICALLY.

If we assume that the magnetic rock has a uniform strike in any direction, a vertical dip and a surface width or thickness equal to $2a$, it is easy to show that the horizontal and vertical components of the rock force are given by the following equations, where x is the horizontal distance of the station of observation from the middle plane of the formation, h is the depth of surface covering, assumed to be uniform, and ϖ is a constant.

$$\frac{H'}{\varpi} = \log \frac{h^2 + (x+a)^2}{h^2 + (x-a)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$\frac{V'}{\varpi} = 2 \left\{ \tan^{-1} \frac{x+a}{h} - \tan^{-1} \frac{x-a}{h} \right\} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

In equation (6) $\frac{H'}{\varpi} = 0$ when $x = 0$; therefore a point of no deflection of the horizontal needle is found vertically over the middle point of the magnetic rock. It is also evident that at corresponding stations on opposite sides of the middle point, the horizontal components are equal, but act in opposite directions.

To obtain the points of maximum or minimum values of the horizontal component, we differentiate the right-hand side of equation (6) with respect to x, and place the result equal to zero. This gives

$$x = \pm \sqrt{h^2 + a^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

which determines two points, at equal distances from 0 on opposite sides of the rock, at which the horizontal component has maximum values. Writing for x the measurable distance d, and squaring, we have

$$d^2 = h^2 + a^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The thickness of the magnetic formation is therefore always less than the distance between the points of maximum horizontal deflection, except when $h = 0$, or the rock is uncovered, in which case the thickness and separation of the maxima are the same.

By differentiating the right-hand side of (7), with respect to x, it is easy to show that V′ has a maximum value when $x=0$. When the rock strikes north and south, this also corresponds to a minimum value of H_r, as has already been shown; and, therefore, by a reference to equation (5) it is readily seen that a point of maximum dip coinciding with a point of no horizontal deflection is in that case found over the middle plane of the buried magnetic rock.

Where the strike is inclined to the meridian, the points of maximum dip and zero deflection will not coincide, since the maximum value of V′ does not occur at the same station as the minimum value of H_r. As has already been shown, H_r is a minimum when $H'=H \sin \beta$ (β being the angle of the strike), and this is in general on the side of the rock on which the angle made with an east and west traverse is obtuse. The point of maximum dip will be situated on the same side of the rock between this station and the point of no horizontal deflection, and will approach the latter as the strike approached the meridian, and also as V′ increases relatively to H′. With strongly magnetic rocks the points of no deflection and maximum dip practically coincide on maps platted to the scale of 4 inches to the mile, except where the strike is nearly east and west.

5. HORIZONTAL AND VERTICAL COMPONENTS WHEN THE MAGNETIC ROCK DIPS AT AN ANGLE.

Under the last heading it was assumed that the magnetic rock dips vertically, and that it continues indefinitely downward at this angle. In consequence of this assumption, and also of the conception of the manner in which magnetism is distributed through magnetic rocks, it has been concluded that the north poles of the rock, which repel the north end of the compass needle, are situated so far below the surface that their effect may be neglected. Therefore we have taken into account only the south poles, which are situated at the rock surface.

In the case of rocks which do not dip at high angles this assumption can not safely be made, and the influence of the bottom poles must be taken into account. Since the force of these poles acts in opposite directions from that of the upper poles, and since they are more deeply buried, it would seem that their influence in general must be to diminish the total force which acts upon the needles at any station, and therefore that the

deflections both of the horizontal and dip needles caused by the same rock should be less in amount, ceteris paribus, where that rock dips at a low angle than where it dips at a high angle.

In the course of the field work certain peculiar deflections of the needles were encountered in traverses across rocks dipping at moderate or low angles. These were not thoroughly understood at the time, but the cause was believed to be connected with the angle of dip of the rock. For example, it was found along traverses crossing certain north-and-south-striking rocks, which were known to have a westward dip that may have been either high or low, that the two points of maximum deflection of the horizontal needle were not situated at equal distances from the point of no deflection between them, but that the distance of the western maximum was much the shorter. It happens in this region that no east-dipping rocks occur which are so far removed from other magnetic formations as to be out of range of their possible influence, but, so far as they go, traverses across these showed that the nearer maximum was situated on the eastern side of the point of no deflection. It therefore seemed probable that the cause of the inequality in the distances from the zero point to the maxima was the dip of the rock, and that the dip was in the direction of the nearer maximum.

If the magnetic formation has a surface width $= b$, is uniformly buried to the depth h, and dips at the angle $\varDelta$, then, if $\lambda = \tan \varDelta$, it may be shown that the horizontal and vertical components at any point P, the horizontal distance of which from the lower edge of the formation is x, are given by the following equations:

$$\frac{H'}{\varpi} = \frac{\lambda^2}{1+\lambda^2} \log \frac{h^2+x^2}{h^2+(x-b)^2} + \frac{2\lambda}{1+\lambda^2}$$

$$\left\{ \tan^{-1} \frac{x-b-\lambda h}{\lambda x - \lambda b + h} - \tan^{-1} \frac{x-\lambda h}{\lambda x + h} \right\} . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$\frac{V'}{\varpi} = 2 \left\{ \tan^{-1} \frac{x}{h} - \tan^{-1} \frac{x-b}{h} \right\}$$

$$+ \frac{\lambda}{1+\lambda^2} \log \frac{h^2+x^2}{h^2+(x-b)^2} + \frac{2}{1+\lambda^2}$$

$$\left\{ \tan^{-1} \frac{h(1+\lambda^2)-\lambda(1+x)}{\lambda^2(1+x)} - \tan^{-1} \frac{b+\lambda\, h-x}{h-\lambda\, b+\lambda\, x} \right\} \quad . \quad . \quad . \quad (11)$$

If $\lambda=\infty$, and the coordinates are referred to axes in the middle of the rock, these equations reduce to equations (6) and (7).

By differentiating the right-hand side of equation (10), placing the result equal to zero, and solving for x, the positions of the stations at which H′ is a maximum may be determined. This gives:

$$x=\frac{\lambda\, b+2\,h}{2\,\lambda}\pm\frac{(\lambda^2 b^2+4\,\lambda^2\, h^2+4\,h^2)^{\frac{1}{2}}}{2\,\lambda} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Calling the difference of the roots, or the measurable distance between the maxima, $2\,d$, and substituting for b its value $\frac{2\,a}{\sin \varDelta}$, $2\,a$ being the true thickness of the rock, we have:

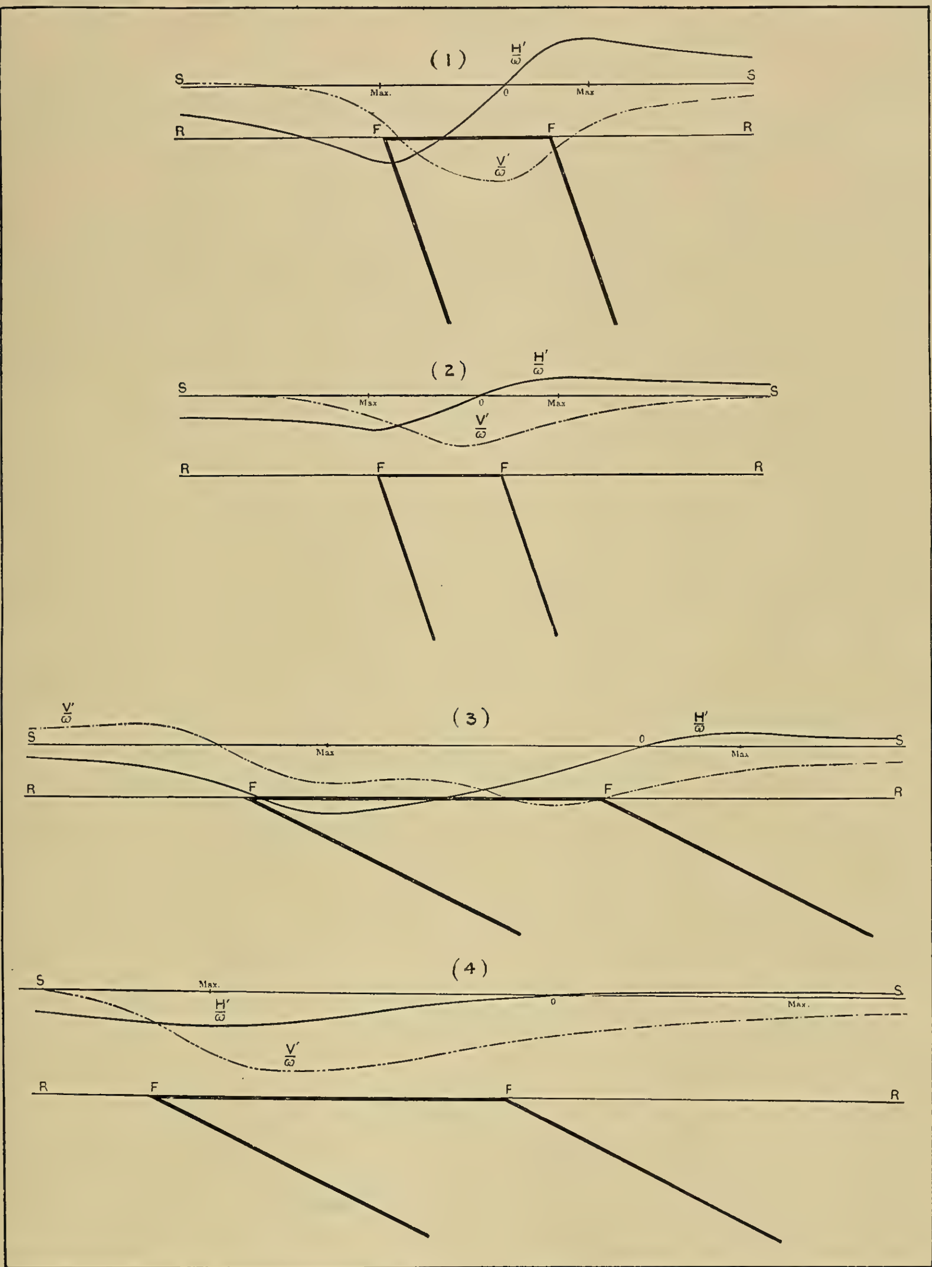
$$d^2=\frac{h^2+a^2}{\sin^2 \varDelta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

For rocks of high dip, therefore, the distance between the maximum points is but little greater than it would be were the dip vertical, and it increases inversely as the angle of dip.

A general algebraic determination of the points at which H′ is 0 and V′ is a maximum is impossible, since it involves the solution of equations of a degree higher than the fifth. However, by assuming numerical values for λ, h, and a (or b) curves expressing the relations between $\frac{H'}{\omega}$ and $\frac{V'}{\omega}$ and x can be plotted, from which the maximum and zero points can be determined in any desired number of special cases.

Let us first assume that $\lambda=3$ (or that the rock dips at an angle of about 70° 34′), $h=2$, and $a=6$. The ordinates to the curves of fig. 1, Pl. XLVII, give the values of $\frac{H'}{\omega}$ and $\frac{V'}{\omega}$ corresponding to different values of x. The ordinates to $\frac{H'}{\omega}$ do not represent the deflections δ of the horizontal needle from the meridian, but quantities that are connected with those deflections by equation (1). The deflections, however, vary as H′ varies, and will have maximum and minimum values at the same points.

From this figure it appears, first, that the nearer maximum is situated on the dip side of the rock; secondly, that the point of no deflection is not over the middle plane, but is nearer the upper edge; thirdly, that the horizontal force of the rock is numerically less at the nearer than at the more



RELATIONS OF MAGNETIC BEDS TO VARIATION AND DIP.

distant maximum, and, fourthly, that the distance between the maximum points is nearly the same for the inclined rock as for the vertical.

In Pl. XLVII, fig. 2, the constants have the same numerical values as before, except h, which now $=4$ instead of 2. The rock is thus buried to twice the depth of the former case. The same conclusions are true for this case as for the first. The zero point is still nearer the upper edge of the rock, and the maxima are farther apart.

Let it next be assumed that $\lambda=0.5$ (or that the rock dips at an angle of about 26° 34′), $h=2$, and $a=6$. These data lead to the curves of Pl. XLVII, fig. 3, in which, as in the case of the rock ot higher dip, the maximum points are unsymmetrical to the point of no deflection, the nearer lying on the dip side.

In Pl. XLVII, fig. 4, we have a rock of the same thickness and dip at a depth $h=4$; and the same conclusions hold true.

From these four curves, which represent formations dipping at high and moderately low angles, and buried to depths which are in the one case small and in the other great, relative to the thickness, it is probably safe to draw the following general conclusions:

(*a*) The direction of dip of a magnetic formation is toward the nearer and (for north-and-south-striking rocks) the numerically smaller maximum.

(*b*) The point of no deflection between the converging maxima is not situated over the middle plane of the formation, but is nearer the upper edge. But with increasing depth and diminishing angles of dip, this point may pass beyond the upper edge.

(*c*) With slightly inclined rocks, for moderate depths of surface covering, the disturbances are spread out over a much wider zone on each side, and the maxima are less sharp, particularly the maximum on the dip side. Under these circumstances irregular and anomalous deflections would be expected in practice, as will be seen in the following sections.

(*d*) The curves of the vertical component show maximum values near the zero value of the horizontal component only in the case of the rock of high dip. In the case of the rock of lower dip, the vertical component has a negative value, or is directed upward over a wide zone on the side of the rock opposite to the dip side. Over this zone the readings of the dip needle will be less than normal, or even negative if $V' > H \tan \theta$. This is in accordance with the facts of observation.

It is also interesting to determine the relative values of the horizontal components at the two maximum points, for different angles of dip, and for different ratios of h to a—that is, for different depths of burial. Fig. 18 shows in graphical form these relations for all angles of dip between 90° and 0° for seven different ratios between $h=\frac{a}{50}$ and $h=4a$. The ordinates to the dotted curves (concave upward) give the relative values of the horizontal component at the maximum point on the dip side (B maximum); those to the full curves (convex upward) the values at the maximum point

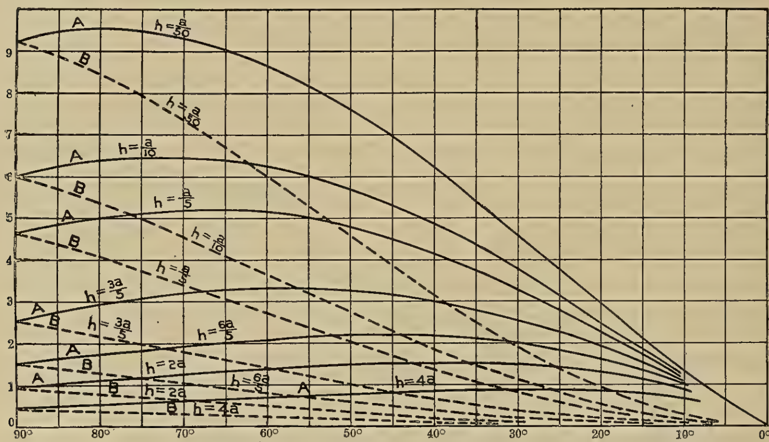


FIG. 18.—Curves showing the relations between the horizontal components at the points of maximum deflection, for rocks dipping at various angles and buried to various depths.

on the other side of the rock (A maximum). These curves show that the horizontal component at the B maximum is always numerically much less than at the A maximum, and that for moderate depths of burial it diminishes very rapidly at both points with small angles of dip.

6. DETERMINATION OF DEPTH.

The relations between the dip and thickness of a magnetic rock, the distance between the horizontal maxima, and the depth of covering are given in equation (13). By assuming numerical values for Δ, and either for a, the half thickness of the rock, or for d, the half distance between the maximum points, it is easy to plot the curve which expresses the relations

between the other two quantities. If d is taken as the constant, the equation represents a circle; if a, it represents a hyperbola.

This equation may have a useful application in making it possible to judge, in advance of actual test pitting, of the probable depth of surface covering over a magnetic rock, for which the original assumptions are fulfilled, and the numerical values of $\varDelta$, a, and d are determinable. It will be remembered that the assumptions upon which equation (13) rests are the fundamental ones of Section III, and also that the rock has a uniform strike. In practice, the uniformity of the strike can be established by other traverses on each side of the one in question, and $\varDelta$, the angle of dip, may usually be determined by the outcrop of other formations in the same series.

For any practical application it is also necessary that a (half the thickness of the rock) and d (half the distance between the stations at which the horizontal component is a maximum) should be known. From an inspection of the equation it is evident that any close determination of h, except for great depths of covering, depends upon very precise knowledge of the ratio between a and d. The practical difficulties in the way of the measurement of a and the ever-present probability that the rock may vary from point to point, not only in actual but in effective magnetic thickness (which is what a actually signifies), make it clear that for the most part h can only be found approximately. Also, in the case of a rock striking due east and west the methods fail, from the fact that $2d$ can not be determined on the ground.

The determination of h is therefore hedged in with important limitations; yet in many cases the information supplied by the equation may be very useful. The difficulties in the way of measuring a are disposed of in the event that along one traverse on the strike of the rock h is known, as it may be, by the sinking of a test pit. This value of h at once gives a value of a, which may be used on other traverses across the same rock with much more accurate results, in the lack of disturbing factors, than if a were known only by measurement It should be added that when the traverse crosses the strike of the magnetic rock at the angle γ, the distance d measured on the line of the traverse must be multiplied by sin γ in order to get the value of d to be used in the determination of h, and also that h must be corrected for the height of the instrument.

More general information as to relative depths of burial is also given by the dip curves. It is easily seen that where the superficial covering is small the vertical component of the rock force must remain small, except immediately over the rock. This condition is, therefore, indicated by steep slopes in the dip curves. On the other hand, where the depth of covering is considerable, the vertical component increases slowly and steadily, beginning at stations at a distance from the rock, and the resulting dip curve approaches the maximum with gentle slopes.

7. SUMMARY.

(1) The strike of a magnetic rock is given by the line joining the points on successive traverses, at which the horizontal needle is not deflected from the local meridian between the converging arrows, or at which the dip angles are a maximum. When the rock is vertical, this line lies in the middle plane of the rock and fixes its position. It may be called a line of magnetic attraction.

(2) The dip of a magnetic rock is toward the nearer horizontal maximum.

(3) The thickness of the magnetic formation must, if buried, always be less than the distance between the maximum points.

(4) Where the superficial cover is not very great, a change in the dip of a magnetic rock from moderate or high angles to low angles is attended with a rapid decrease in the values of the horizontal component, with a corresponding decrease in the deflections of the horizontal needle.

SECTION VI. APPLICATIONS TO SPECIAL CASES.

In the preceding section certain general conclusions have been established with regard to the relative positions of the stations at which the horizontal and vertical components of the force of a magnetic rock have maximum and zero values. The deflections produced by these components from the positions which the magnetic needles assume under the action of the earth's force have maximum and zero values at the same stations at which the components have maximum and zero values, and therefore the conclusions as to the relative positions of these points are true for any angle of strike. But certain numerical relations between the deflections depend upon the orientation or strike of the magnetic formation and upon the direction of dip, and these will now be considered.

1. THE MAGNETIC ROCK STRIKES EAST OR WEST OF NORTH AND DIPS VERTICALLY.

Let us first take the case of a rock striking east of north. At the stations within range of the local influence on the east side of such a rock belt the horizontal needle is pulled west of the meridian, reaches a westward maximum, then points north, then on the west side of the belt, east of the meridian, and reaches an eastward maximum. It is observed, however, that the westward deflections on the east side of the belt are generally not so great as the corresponding eastward deflections on the west side of the belt. The reason for this is easily seen. At each station east of the belt the local pull acts along the normal to the belt drawn through the station. This normal makes with the local magnetic meridian an acute angle. The needle will come to rest within this acute angle along the line of the resultant of the horizontal components of the two forces, the earth's and the local force, which determine its position. However strong the local pull may be, the horizontal needle can not be deflected past the normal.

At the corresponding stations on the west side of the disturbing belt the local pull also acts along the normal from the station to the belt, and has the same numerical value. But in this case the normal makes an obtuse angle with the magnetic meridian. For two points equally distant from the magnetic belt, one on the east and the other on the west, the resultant for the western point will, therefore, make a larger angle with the meridian than that for the eastern.

On the other hand, when the rock strikes west of north, it is observed that the horizontal deflections are greater on the east side than on the west, and the explanation is entirely similar to that given above.

The dip-needle observations at the same stations show general phenomena quite like those in the case in which the strike of the rock coincided with the meridian. They gradually increase to a maximum near the station, where the horizontal needle stands at zero between the converging arrows, and gradually decrease from this maximum on the other side. It is noted, however, that the readings are not equal at corresponding stations on opposite sides of the maximum. When the strike is east of north, the western station shows a higher dip than the eastern; when the strike is

west of north, the eastern station shows a higher dip than the corresponding station on the west. Generally stated, then, the stations on that side of the magnetic rock on which the angle between the strike of the rock and the line of traverse is obtuse show greater dip angles than the corresponding stations on the side on which this angle is acute. As the angles of dip are represented graphically by a continuous curve, this is the same thing as saying that the dip curve is steeper on the side of the acute than on that of the obtuse angle.

These facts are easily explained by the following considerations. The vertical components tend to lower the needle, and would carry it to a vertical position except for the action of the horizontal forces, which tend to keep it horizontal. At any station on the acute-angle side of the magnetic belt the resultant of the two horizontal components is larger than at the corresponding station on the obtuse-angle side, the two being represented by the longer and shorter diagonals of a parallelogram. Since the vertical forces are the same at the two stations, it follows that on the obtuse-angle side the angle of dip must be larger than on the acute-angle side. Or, expressed algebraically, since H_r is the only variable on the right-hand side of equation (5) it is evident that tan α, and therefore α, the angle of dip, increases with a decrease in H_r.

If the rock dips at an angle less than 90°, these results are either intensified or greatly modified, depending upon the direction of dip. It was shown in the last section that the horizontal component of the rock force is smaller on the dip side. If the strike and dip are both toward the same side of the meridian (e. g., if the strike is northwest and the dip southwest), it is evident that the numerical difference between the deflections of the horizontal needle on the two sides of the rock will be still greater than if the rock were vertical. On the other hand, if the strike and dip are toward opposite sides of the meridian (e. g., if the strike is northeast and the dip northwest), the difference between the deflections on the two sides is less than for a vertical dip, or may even be reversed.

The deflections of the dip needle in the case of rocks dipping at angles less than 90° are also greatly influenced by the direction of dip. If strike and dip are toward the same side of the meridian, the difference noted above in angle of dip on the two sides of the rock is neutralized, and the dip curve tends to become symmetrical; while if they are toward opposite

sides of the meridian, the difference is increased. It is to be noted that the influence on both instruments of the direction and angle of dip of the rock becomes weakened with an increase in surface covering.

2. THE MAGNETIC ROCK STRIKES EAST AND WEST.

When a vertically dipping magnetic rock strikes east and west, or nearly so, the traverse lines must be run north and south so as to cross it as nearly as possible at right angles. In approaching such a belt from the south the instruments give little warning. The readings of the horizontal needle show either no deflections, or else very slight deflections, from the magnetic meridian. Past the middle of the formation the horizontal needle is strongly deflected, often through an angle of 180°, so that it may point due south. But as the magnetic rocks having this strike which were encountered in our work were not deeply buried, and had also quite irregular upper surfaces, generally the needle pointed either east or west of south on account of the weight which the nearness to the surface gave to the adjacent material, either from the irregular distribution of magnetite or from the protrusion of small masses above the general level. Continuing north, the horizontal deflections gradually diminish and eventually disappear.

The behavior of the horizontal needle is explained in the same way as in the preceding cases. The position of the needle at any station is determined by the resultant of the horizontal components of the two forces—the earth's force and the rock force—that act upon it. South of the magnetic rock these two components act in the same direction and essentially in the same line, since the magnetic meridian practically coincides with the true meridian. The resultant, therefore, is equal to their sum and coincides with them in direction, and consequently there is no deflection. North of the magnetic rock the two horizontal components act in opposite directions, and when they are in the same line the needle takes up its position in the direction of the greater, which determines that of the resultant; when H' is greater than H (which often happens near and north of the rock) this direction is due south. When the two components do not act in exactly the same line, the needle will point east or west of south at an angle which depends on the angle between the two forces and their ratio.

Still farther north the horizontal component of the rock force diminishes rapidly and we consequently first pass through a zone of large and

diminishing deflections to the east or west, depending on the side of the meridian on which this component falls; and finally, when it becomes insensible, the needle rests again in the meridian.

In the case of a rock striking east and west, the points at which the horizontal component of the magnetism of the rock has maximum values become indeterminate by the methods hitherto described, from the fact that throughout the traverse the two components act in or nearly in the same line, and the deflections from the local magnetic meridian, therefore, do not indicate the relative strengths at different stations of the horizontal component of the rock force.

The dip-needle readings for an east-and-west-striking rock are as follows: At some distance south of the rock the angles are constant at the index error. As the rock is approached, the angles of dip depend upon the depth of burial. If the surface covering is considerable, an increase in the dip angles begins at a considerable distance away, and progresses continuously as the magnetic belt is approached. If the rock is near the surface, the dip needle shows either the constant index error or else angles of dip less than the index error for all stations south except those very near the southern margin of the rock. The maximum reading is attained north of the middle plane of the rock, at a distance from it which also depends upon the depth of covering. Farther north the dip angles decrease slowly and are in general greater than at the corresponding stations south. The form of the dip-curve, therefore, shows a steeper slope south of the magnetic rock than north of it. The reasons for these differences will be evident from the following considerations.

Let it be supposed, for the sake of simplicity, that throughout the north-and-south traverse the two horizontal components act in the same line in the meridian. At any station south of the magnetic rock they act in the same direction, and their resultant will be their numerical sum. At the corresponding station north they act in opposite directions, and their resultant will be their numerical difference. The angle of dip is given by equation (5):

$$\tan \alpha = \frac{V' + H \tan \Theta}{H_r}$$

For the two corresponding stations, V' will be the same. The other quantities are all constants except H_r. For the south station $H_r = H' + H$;

for the north station, $H_r = H - H'$, where H and H′ are, respectively, the horizontal components of the magnetism of the earth and of the rock, as before. The numerator of the right-hand side of the equation will be the same for both stations, while the numerical value of the denominator will be less for the north station than for the south. Consequently tan α, and therefore α, will be greater for the north station.

For great depths of superficial covering, however, these differences become almost imperceptible, owing to the fact that H′ is so small that H_r is essentially the same at the two corresponding stations. The tendency, therefore, as h increases is for the dip curve to become symmetrical.

In the special case in which $H' = -H$, $H_r = 0$, and the dip needle stands at 90°. This can only take place north of the rock, and may, depending on the strength of H′, be found at two stations, one on either side of the station at which H′ is a maximum. At the same stations the horizontal needle is not acted on by any unbalanced force, and rests indifferently in any position.

The dips less than normal which are often observed at stations south of a magnetic rock which lies very near the surface are also easily understood by a reference to equation (5). At these stations the resultant pull of the rock is so nearly horizontal that the vertical component V′ is very small in comparison with the horizontal component H′. If V′ is a negligible quantity, equation (5) becomes

$$\tan \alpha = \frac{H}{H + H'} \cdot \tan \theta$$

In such cases the angle of dip is therefore less than the index error. With north or south dipping rocks, where V′ is negative, tan α becomes negative when $V' > H \tan \theta$.

3. TWO PARALLEL MAGNETIC FORMATIONS.

The cases so far considered have involved only one belt of magnetic rock, which has been assumed to have a uniform dip in one direction, or, in other words, to be a monocline. In practice, however, owing to complexities of structure and other causes, which will be considered hereafter, it frequently happens that two or more approximately parallel belts are found within the range of one another's influence. Under these circumstances

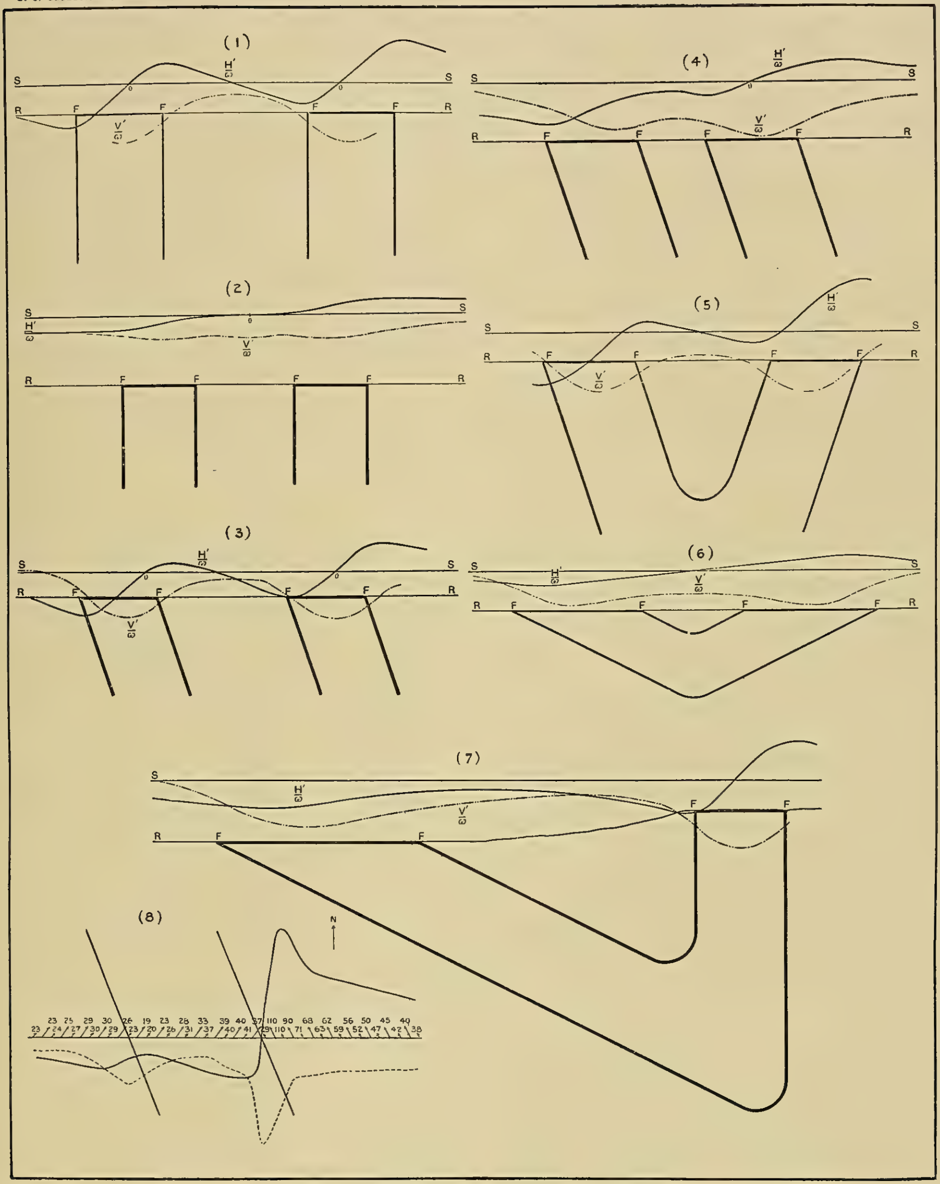
the effects produced upon the magnetic needles are correspondingly complicated.

For the purposes of illustration it is sufficient to consider a few extreme cases, and to represent the values of $\frac{H'}{\omega}$ and $\frac{V'}{\omega}$ for these graphically. Let it first be assumed that the two parallel belts are vertical, that the distance between them is 8, and that $a=3$, and $h=2$. This represents the conditions when the distance of separation is large compared with h. The ordinates to the curve of Pl. XLVIII, fig. 1, give the values of $\frac{H'}{\omega}$ which correspond to the different stations of observation. Those parts of the curve which are above the horizontal axis of coordinates represent the portions of the traverse in which H′ is directed toward the west; the parts below, those in which it is directed toward the east. It is seen that besides the middle point there are two other points of no horizontal deflection, which do not exactly correspond with the points vertically over the middle of the magnetic formations, but are somewhat nearer the adjoining edges; and also four points of maximum deflection, one on each side of each rock. The maximum points inside of the two formations have smaller deflections than those outside, as shown by the relative lengths of the ordinates to the curve, and also between the inside maximum points the horizontal components are directed away from the middle point.

The curve of $\frac{V'}{\omega}$, represented by the dotted line, has two maximum values, which fall nearly over the two rocks.

If next we assume that the distance between the rocks is 8, and that $a=3$, and $h=8$, we obtain the curve of Pl. XLVIII, fig. 2, which represents the value of $\frac{H'}{\omega}$ when h is large compared with the distance of separation. This case shows but one point of no horizontal deflection between the two rocks and but two points of maximum deflection, one on the outside of each.

The curve of $\frac{V'}{\omega}$, represented by the dotted line, shows the interesting feature of three maximum points, one at the center and one over each rock. If h were relatively a little greater, these would evidently coincide at the center.



RELATIONS OF MAGNETIC BEDS TO VARIATION AND DIP.

If the two parallel formations are not vertical, but dip in the same direction at the same angle, the resulting curves are somewhat different. Pl. LXVIII, figs. 3 and 4, show two cases in which the elements are the same, except the depth of covering and the thickness of the intervening nonmagnetic material. Here the rocks dip at an angle of 71° 34′. and the width at the rock surface is 6.3 for each.

In fig. 3, Pl. XLVIII, where $h=2$ and the width of the nonmagnetic bed is 10.7, and the covering is, therefore, relatively small, the presence of two rocks is distinctly shown by the curves of both components, and the chief result of their interaction is to introduce an additional point of no horizontal deflection between them, on each side of which the horizontal arrows diverge. The positions of the maximum and of the other zero points are hardly disturbed, and consequently the direction of dip is very clearly indicated.

In fig. 4, Pl. XLVIII, where $h=4$ and the formations are separated by nonmagnetic material 4.7 wide, there is but one zero point, nearly over the middle of the upper formation, toward which the pointings of the horizontal needle converge. West of this are two points of maximum eastern deflection, between which a faint minimum represents the backward pull of the lower formation.

If the two magnetic formations are parallel in strike, but dip toward each other at equal angles, the resulting curves of the two components are shown in Pl. XLVIII, figs. 5 and 6. Fig. 5 illustrates the effects on a syncline with steeply dipping sides, the superficial covering being relatively shallow. These conditions result in a point of no horizontal deflection over the middle of the trough with diverging arrows on each side, and besides a point of no horizontal deflection over each rock, toward which the arrows converge. The positions of the two maximum points for each rock, and of the zero between them, is nearly the same as if the other rock were absent, and consequently the fact that the rocks dip toward each other is clearly indicated by the unsymmetrical distances.

In fig. 6, Pl. XLVIII, the depth of the rock surface is much greater relatively to the inside distance between the legs of the syncline, and the dip is flatter. In this case there are but two points of maximum deflection, one on each side of the syncline, and but one point of no deflection, over the middle of the trough. The maximum points represent the outside maxima

of the former case, and the result of the interaction of the two legs is to increase the numerical values of these, as well as to bring them nearer together. It is evident that the deflections of the horizontal needle in this case could hardly be distinguished from those that would be produced by a single vertical formation buried to a considerable depth.

Let it next be supposed that the two rocks dip toward each other at different angles, the strikes remaining parallel, and also that the rock of lower dip is buried to the greater depth. This, then, is a case in which the magnetic effect of one limb of the syncline is much stronger than that of the other.

In Pl. XLVIII, fig. 7, the curves of the two components are given for the special case in which the right-hand limb of the synclinal dips at an angle of 90°, and has a surface covering $h=2$, while the left-hand limb dips at an angle of 26° 34′, and has a surface covering $h=4$. It is interest-

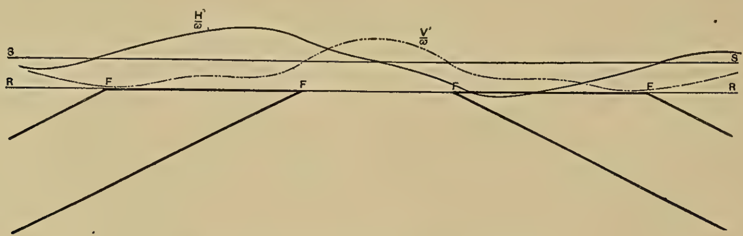


Fig. 19—Truncated-anticlinal fold with gently dipping limbs.

ing to compare the theoretical results of this figure with the curves of Pl. XLVIII, fig. 8, which represent deflections actually observed, and not components.

In the latter figure the strike of the two rocks is represented by the heavy lines. The two rocks are the same formation, brought up by folding on opposite sides of a synclinal trough. The synclinal is slightly pushed over, so that the eastern rock dips nearly vertical, while the western has a much lower dip toward the east, and is also more deeply buried. These facts rest on independent evidence, yet they might all be inferred from the observations recorded in this figure.

The dip curve in this case shows two distinct maxima, a smaller under

the zone of retardation and a larger over the point of no horizontal deflection, which correspond respectively to the two magnetic rocks.

If the two formations are parallel in strike, but dip away from each other, the curves of the horizontal and vertical components for different angles of dip and different relations of thickness and depth of covering are shown in figs. 19 and 20. In fig. 19 the formations are widely separated, h is relatively small, and the angles of dip are equal and low; the interaction of the two rocks therefore extends over a narrow zone only, and the curves of the components clearly indicate the presence of two formations and the direction of dip of each. In fig. 20 the anticlinal is so truncated that magnetic material occupies the whole space on the rock surface between the outer boundaries of the two formations. The angles of dip are equal, and are higher than in the preceding case, while the depth of covering is relatively much greater. The horizontal component is zero in the axial plane of the anticlinal, and has maximum values at two points, one on each side of the zero. The vertical component is a maximum at one point, also in the axial plane. The deflections produced by these conditions could not be distinguished in practice from those produced by a single vertically dipping formation.

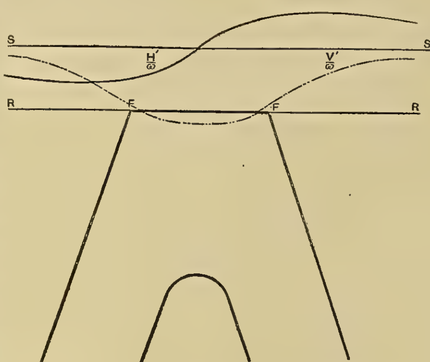


Fig. 20.—Truncated anticlinal fold with steeply dipping limbs.

In general, therefore, when two magnetic formations lie within range of each other's influence, the deflections are determined by the relative magnetic strengths of the two rocks, by their distance apart, by their strike and dip, and by their depth of burial. It is evident that for certain given relations among these factors the special cases above described will occur, and it is found that they really do occur in practice. For other relations it is not possible to make a general statement either as to the number or the position of the maximum and minimum points.

SECTION VII. THE INTERPRETATION OF MORE COMPLEX STRUCTURES.

The existence of two parallel belts of magnetic rocks may be accounted for geologically in more than one way. They may represent two distinct formations occurring at different horizons in the same series, or they may represent the same formation either duplicated by folding or faulting or separated into two parts by the intrusion of a sheet of igneous rock parallel to its bedding. Since, then, two magnetic lines, the existence of which has been established by observation, may have more than one interpretation, the discrimination of these cases, when possible, is of special importance.

The question whether any given case belongs to the first of these categories can generally be settled only by following the lines of attraction into a district which affords a geological section across the formations involved, or by the occasional outcrop of the rocks which give rise to the disturbances, in which case lithological resemblances or differences, the relations to other formations, and the observed structure will decide the matter one way or the other. In the special case in which either or both lines can be followed completely round an anticlinal dome or a synclinal basin, which of course can only rarely happen, the question would be settled affirmatively, even if outcrops were entirely lacking.

In the other instances the magnetic observations themselves often give means of discrimination, even when the outcrops are so few or so obscure as to be in themselves indecisive. It is characteristic of the folds in the pre-Cambrian rocks of this region that the axes are not usually parallel with the horizon for long distances, but are often inclined to it; in other words, when followed for greater or less distances they pitch. The outcropping edges of any formation involved in an anticlinal or synclinal fold which has been cut by a plane of denudation will be parallel to each other wherever the axis of the fold is horizontal, but will approach each other where the axis is inclined. In an anticlinal fold they converge in the direction in which the axis sinks, while in a synclinal they converge in the direction in which the axis rises. If the formation is a magnetic one, conformably placed between beds of nonmagnetic character, the magnetic lines to which the outcropping edges give rise will therefore run parallel to each other when the axis is horizontal and will converge or diverge when the axis pitches. The convergence or divergence takes place gradually, since the angles of pitch usually are not large.

In the case also of a single formation which stands on edge and has been split by the intrusion of a sheet of eruptive rock parallel to the bedding planes, the magnetic observations will often show two parallel lines, which, at the extremities of the eruptive rock, where it wedges out, merge into one.

In general, therefore, two parallel magnetic lines which represent two distinct formations preserve their identity, and do not pass into each other; when, however, they represent the same formation, they will often come together if followed far enough. The principles which have already been applied to the analysis of simpler cases are useful in discriminating among the three cases of convergence.

1. PITCHING SYNCLINES.

Let us first consider a pitching synclinal fold, which is represented in plan and by successive cross sections in fig. 21. It is evident that on the lines of traverse along Sections I and II the deflections of the needle will observe the usual sequence for two parallel belts, the details depending upon separation and depth of covering, while on lines along Sections III, IV, and V the phenomena will be those caused by a single belt of magnetic rock. Also, on account of the rise in the axis, the south poles of the rock are brought continually nearer the surface on these successive cross sections, and therefore the two components of the rock force will be smaller for each traverse than for the one preceding. Since the magnetic material comes to an end at A, it is no longer true that there is as much magnetic material on one side of these sections as on the other. Consequently the horizontal component due to the pull of the rock does not become zero at any point along these sections, but for every station has a positive numerical value and acts in the general direction in which the synclinal pitches. At the station in the plane of symmetry of the fold this

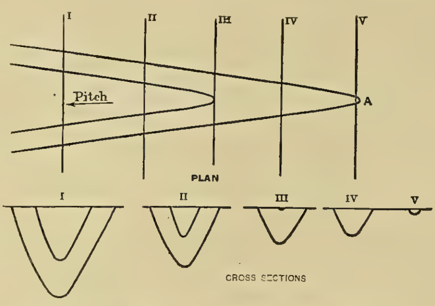


Fig. 21.—Plan and cross sections of a pitching syncline.

component acts parallel to the axis. The direction and amount of the deflection depend upon the direction of strike and pitch of the synclinal.

Let us suppose, first, that the axis of the synclinal strikes north and pitches north. In this case Section I, in fig. 17, is the most northern, Section V the most southern.

The traverses along Sections I and II display the usual phenomena for two parallel belts. East of the eastern limb and west of the western the horizontal needle will be deflected toward the syncline. Between the two limbs there will be at least one point of no deflection, and frequently, depending upon the relations between the depth of burial and the thickness of the intervening nonmagnetic material, either two other points of no deflection or two zones of retardation, one on each side of this middle zero.

Along Sections III, IV, and V there will be but one point of no deflection of the horizontal needle, which will correspond with the axial line of the fold. Since this axis is north and south, and so coincides with the magnetic meridian, the horizontal component of the rock force coincides in direction with the horizontal component of the earth's pull, and consequently there is no deflection of the horizontal needle. For other stations east and west of the central station the deflections are toward the west and east, with the usual maximum points.

The deflections on successive sections south grow smaller, since the angle between the two horizontal components progressively diminishes. The relative value of the horizontal component of the rock force also progressively diminishes, since the thinning of the magnetic material due to the rise in the axis of the fold brings the buried north poles into prominence. Therefore the deflections of the horizontal needle after the magnetic rock has been left behind very soon become imperceptible.

The dip needle deflections for the northern sections, I and II, reach their maximum values at the usual points, over the central zero and near the outside zeros or points of retardation. For the southern sections the dips grow less, since the horizontal restoring couple due to the rock has always a positive numerical value, and also because the vertical component of the rock force diminishes, owing to the nearness of the south poles. As the section approaches the limits of the magnetic material the points of maximum dip become less and less clearly defined, and the dip curve passes into an irregular line, slightly depressed below the line of no deflection.

The reasons for this are, of course, obvious from what has been said above.

In the case of a synclinal fold pitching south, Section I (fig. 17) becomes the most southern, Section V the most northern, line of traverse. Sections I and II present the same general phenomena as before for both needles. In Sections III, IV, and V the horizontal component due to the rock has a positive value for all stations as before, but in this case acts in a generally opposite direction to that of the horizontal component of the earth's force. Therefore, on these sections we should expect at first greater deflections of the horizontal needle, which would diminish rapidly as the sections approached and passed beyond the northern limit of the magnetic material, but which, for corresponding sections, would be greater than for the northerly pitching fold. The deflections of the dip needle would also be greater for the same reasons.

For a synclinal pitching west, Section I is the most western, Section V the most eastern, traverse. In this case, along I and II, the deflections of the horizontal and dip needles are dependent for their details upon the ratio of depth to distance of separation, but if far enough to the west will show clearly two belts of magnetic material, approximately parallel, and striking approximately east and west. For Sections III, IV, and V, in which the distance of separation is either nothing or relatively small, the phenomena will indicate but one belt. On these sections, owing to the fact that the horizontal component of the rock pull is nowhere zero and has everywhere a general westerly direction, the deflection of the horizontal needle will be westerly throughout, and will reach a maximum north of the east-and-west axial plane of the material, where the angle which it makes with the magnetic meridian is more than 90°.

In accordance with the general principles stated in the discussion of a single belt with the same strike, the angles of dip are in general smaller south of the syncline than north, and the maximum dip is reached at a point north of the axial plane. On sections farther to the east, near the limits of the rock and beyond them, the dip-needle deflections, like those of the horizontal needle, rapidly diminish and soon become imperceptible. These facts are well shown in fig. 22, which represents a series of north-and-south traverses across the Groveland basin, the limits of which are defined by outcrops on the eastern side.

In this figure it is instructive to notice the small dip angles in the sections east of the end of the syncline. In the first of these the dip curve shows a hollow near the axis of the fold or angles of depression less than the normal. This is easily understood upon considering that, since the surface covering is here small, the vertical component of the rock force becomes very small at these stations compared with the horizontal component.

For an eastward-pitching syncline it is obvious that the facts will be entirely similar to those stated above, except that the deflections of the horizontal needle will be toward the east instead of toward the west. This

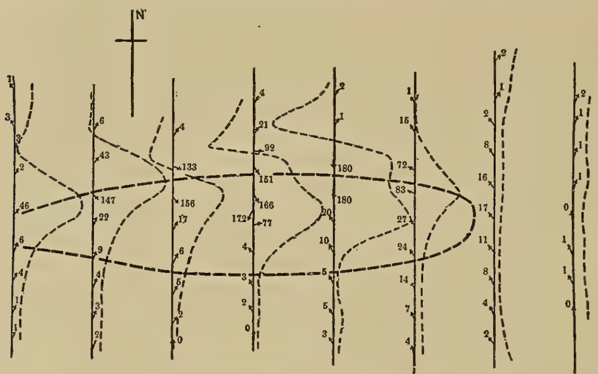


Fig. 22.—Magnetic map of the Groveland Basin.

is also well shown at the western end of the Groveland basin in fig. 22. This basin does not show the phenomena of two lines, however, from the fact that it is so narrow and shallow that it does not include in its interior any overlying nonmagnetic material, and there is accordingly no separation of its rims.

2. PITCHING ANTICLINES.

In the cases of pitching anticlines (fig. 23) the sequence of observations in the area of separation of the rims is very similar to that of pitching synclines. In the zone of coincidence the structural difference in the two cases is that the material does not come to an end, but continues as one band, which, as the axis sinks, is progressively buried to a greater depth.

Therefore, in general, the buried north poles of the magnetic formation are not brought nearer the surface; and this, together with the fact that the material continues on in the line of the axis, produces characteristic phenomena in the magnetic sections.

These phenomena, the details of which can be easily followed out for any given direction of pitch, and need not here be described, show in general two lines of attraction merging into one, which continues in the same direction as a strong line, showing, as it is followed, the peculiarities due to an increasing depth of burial. The points of maximum deflection of the horizontal needle continue to separate from each other on successive sections. The dip curve shows a definite maximum closely corresponding, except for due east-and-west strikes, to the point of no horizontal deflection. Where the axis of the fold is so oriented that these points can be established, they indicate the nature of the fold. If the strike is east and west, in which case they become indeterminate, the continuity of the line and its very gradual decrease in power may give an excellent basis for inference as to the nature of the fold.

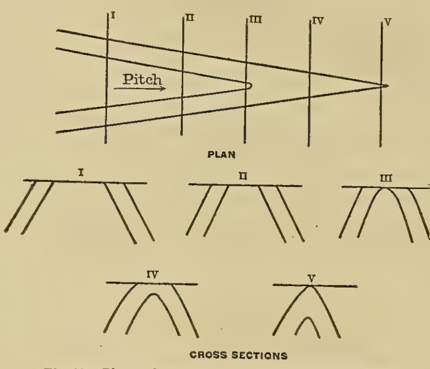


Fig. 23.—Plan and cross sections of a pitching anticline.

3. FORMATIONS SPLIT BY INTRUSIVES.

When a single formation has been split into two by the intrusion of a nonmagnetic igneous rock, there are in the area in which the igneous rock occurs two parallel magnetic formations, which give rise on cross traverses to phenomena the precise features of which depend upon the strike and dip of the formation and upon the relation which the width of the intruded mass bears to the depth of burial. To describe these would involve a mere repetition of what has been said before. Such intruded masses always have a definite limit in length, which is usually not very great. When the limits are reached, the two parallel lines pass into a single line which continues on

in undiminished vigor. Also, such intruded masses are seldom confined to definite horizons for great distances and seldom split the formation into symmetrical halves. Two nearly parallel lines of unequal strength, which, as they are followed, become equal, and then again become unequal, with the stronger on the opposite side, are often, therefore, characteristic phenomena of this case. A good illustration of the unequal division of a magnetic rock at different points along its strike by an intruded sheet which wedges

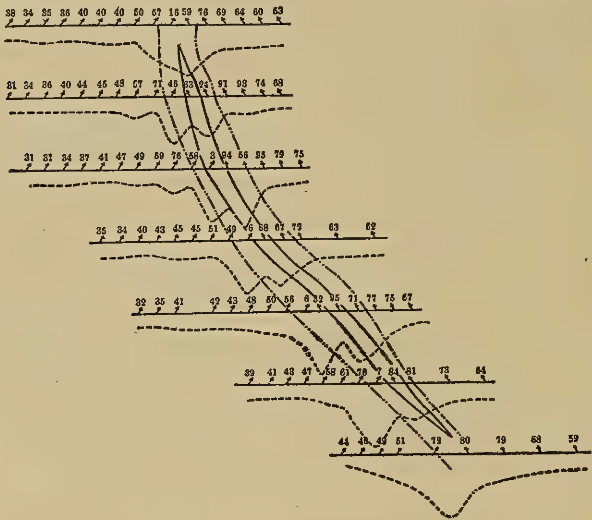


Fig. 24.—Magnetic map of a single formation split by an intruded sheet.

out at both ends is given in fig. 24. Between the second and third traverses from the north end the existence of this sheet has been proved by drilling.

4. SUMMARY.

The means of discrimination among these cases of convergence are therefore founded on the deflections in the critical areas, where the separated bands of magnetic material merge into one. Strong deflections toward the point where they run together, with a rapid disappearance of all disturbances within a short distance of this point, indicate a pitching synclinal

fold. A long continuance of the disturbances, with the characteristic phenomena attending deeper burial, beyond the point of coincidence, indicates an anticlinal fold. A coincidence in both directions and the continuation of the disturbances without diminution indicate an intrusive sheet. To these may be added the delicate criterion which the unsymmetrical distances of the horizontal maxima from the central zero may afford. If in the area of separation the two belts depart from each so far as to be out of range of each other's influence, and it is found on successive cross sections that the nearest maxima are inside the lines of no deflection which directly indicates the position of the rock, it can be concluded that the rocks dip toward each other, and, on the other hand, if the nearer maxima are outside these lines, that they dip away from each other. In the one case a syncline and in the other an anticline would be indicated, and, of course, in either case it would be certain that the phenomena could not be due to an intruded mass.

CHAPTER III.

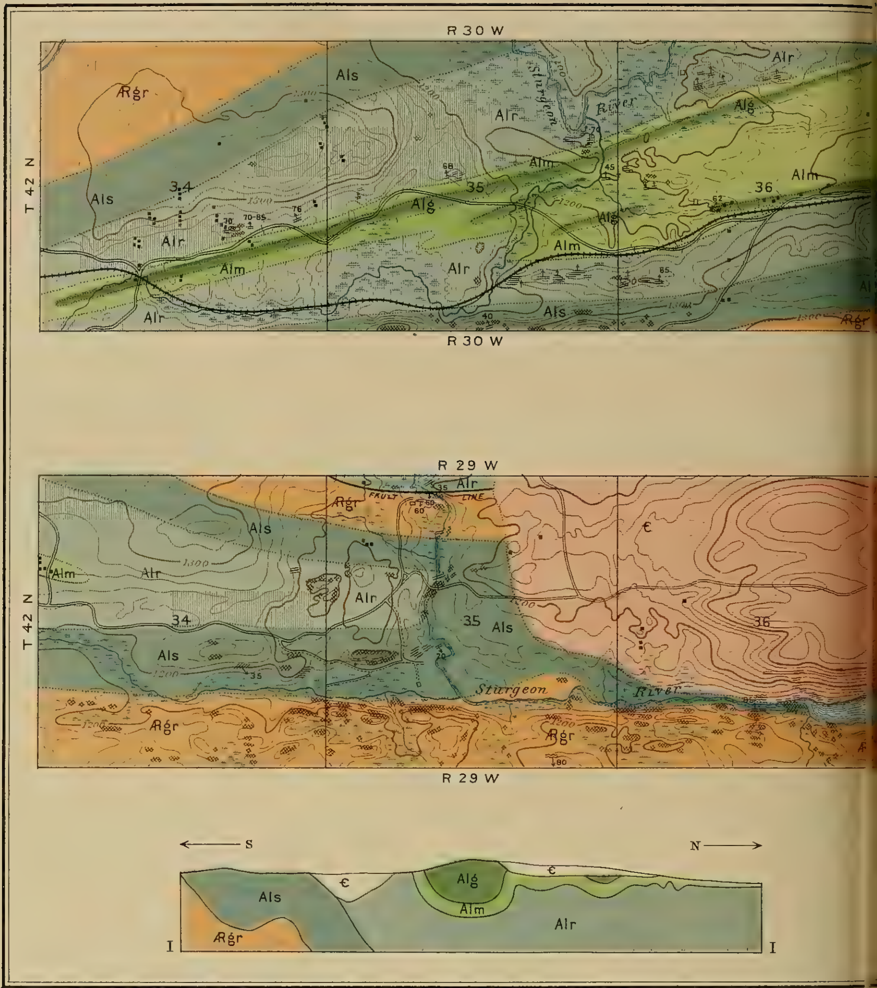
THE FELCH MOUNTAIN RANGE.

SECTION I. POSITION, EXTENT, AND PREVIOUS WORK.

Our map (Pl. XLIX) of the Felch Mountain range includes 12 sections in the southern tier of T. 42 N., Rs. 28, 29, and 30 W., beginning with sec. 33, T. 42 N., R. 28 W., on the east, and ending with sec. 34, T. 42 N., R. 30 W., on the west. The range is known to extend beyond these limits both to the east and to the west. Rominger states[1] that it has been traced 4 miles east of our eastern boundary, and also west of our western boundary to the Menominee River north of Badwater Village. From a hasty reconnaissance of the country to the east it seemed probable that but few additional facts could be determined, because of the swamps and the extensive cover of the Paleozoic sandstone, and these sections were therefore not studied in detail. We were not able to continue the work to the west, on account of the lateness of the season, but it is desirable that this should be done at some future time. The sections surveyed include, however, that portion of the range in which outcrops are most abundant and which has been the principal seat of exploration for iron ore.

The strong magnetic attractions in several of these sections and the prominent outcrops of ferruginous jaspers at Felch Mountain in sec. 32, T. 42 N., R. 28 W., and in sec. 31, T. 42 N., R. 29 W., were early noticed by the United States land surveyors and indicated on the township plats. With the rapid development of the Marquette range after the close of the civil war the attention of miners was quickly drawn to these as to other outlying prospects, with the result that vigorous exploration was begun on this range even earlier than on the Menominee range proper.

[1] Geological report on the Upper Peninsula of Michigan, by C. Rominger: Geol. Survey, Mich., Vol. V, 1895, p. 35.



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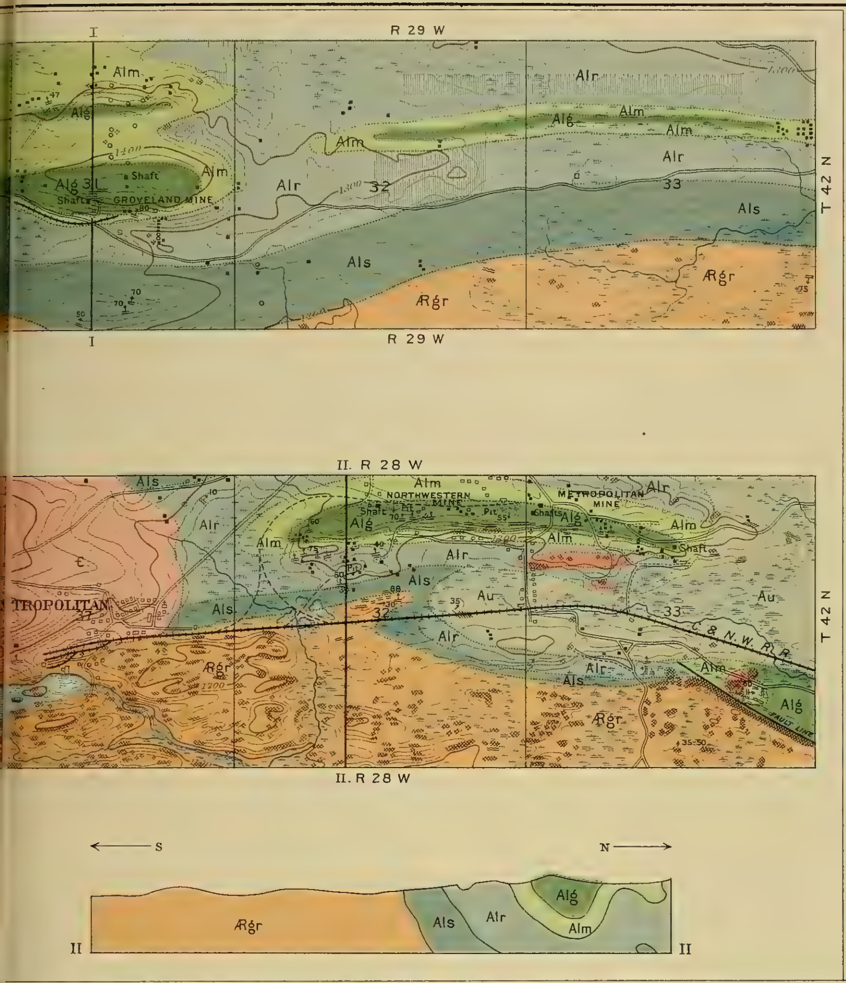

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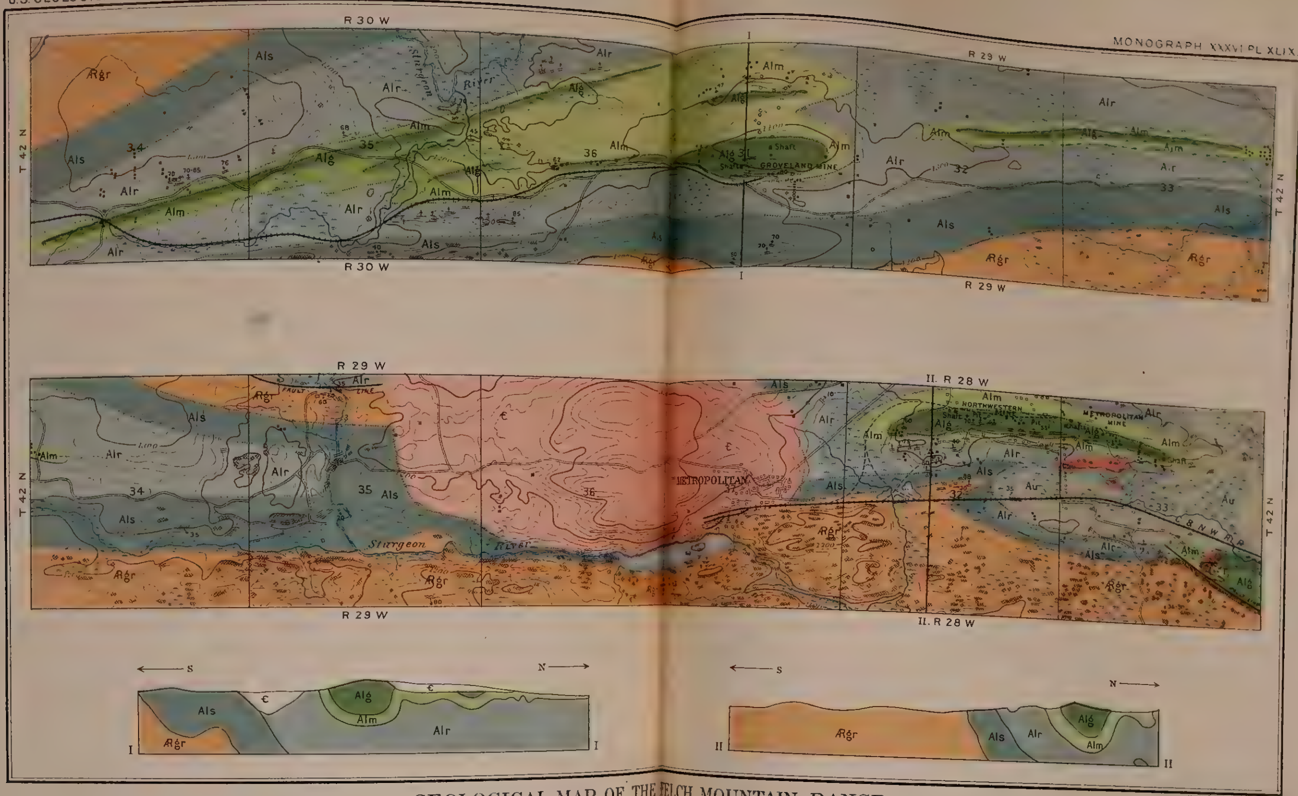

GEOLOGICAL MAP OF THE FELCH MOUNTAIN RANGE

TOPOGRAPHY AND GEOLOGY
BY H. L. SMYTH

SCALE 2 INCHES = 1 MILE   CONTOUR INTERVAL 20 FEET
HORIZONTAL SCALE OF SECTIONS 2 INCHES = 1 MILE   VERTICAL SCALE 1 INCH = 1320 FEET
ELEVATION OF DATUM PLANE 600 FEET

Outcrops ... strike or dip
Outcrops ... strike and dip
Outcrops ... foliation
Test pits ...
Drill holes

ALGONKIAN

ARCHEAN	LOWER HURONIAN				UPPER HURONIAN	INTRUSIVE		CAMBRIAN
Granite	Sturgeon Quartzite	Randville Dolomite	Mansfield Schist	Groveland Formation	Undivided	Diabase	Granite	
Ægr	Als	Alr	Alm		Au			€

The following abstracts of the published literature upon the Felch Mountain range are given as far as possible in the author's words:

1850.

BURT, WM. A. Geological report of the survey, "with reference to mines and minerals," of a district of township lines in the State of Michigan, in the year 1846, and tabular statement of specimens collected. Dated March 20, 1847. Thirty-first Congress, first session, 1849–50. Senate Documents, Vol. III, No. 1, pages 842–875. With maps.

The earliest mention of the part of the Upper Peninsula included within the Felch Mountain range was made by Burt in describing the distribution of the talcose and argillaceous slates of the area covered in the course of his land survey in 1846. He states that the argillaceous slates "are developed in parts of township 42, ranges 29 to 30 west" (p. 846).

The existence of the iron ore in this area was discovered by this explorer.

The first bed discovered of this ore was found while traveling from the Peshakumme Falls, near the Menomonee River, east to Fort River, before it was surveyed in May last, but was not discovered again during the survey. It is believed, however, that this bed of iron ore is not far distant from the corner of townships 41 and 42 N., between ranges 29 and 30 W. It was found in a low ridge about 3 chains wide, course WNW. This ridge appeared to be nearly one mass of iron ore, stratified and jointed; consequently it may be quarried with ease. This ore has generally a granular or micaceous structure, but specular varieties sometimes occur; color, iron black, passing into a steel gray; luster when fresh broken, metallic, but soon oxidizes when exposed to the atmosphere. This is supposed to be an extensive and rich bed of iron ore. The variation of the needle was taken on the east side of the ridge at the crossing of a hunter's trail, and its north end stood S. 82° E. Three or 4 miles west of this, on the north side of a ridge, near a cedar swamp, the variation was N. 45° 30′ W. Probably in this vicinity may be found another extensive bed of similar iron ore (p. 849).

1851.

FOSTER, J. W., and WHITNEY, J. D. Report on the geology and topography of the Lake Superior land district. Part II. The iron region, together with the general geology. Dated November 12, 1851. Thirty-second Congress, special session, 1851. Senate Documents, Vol. III, No. 4; 406 pages; with maps and plates.

Foster and Whitney, in sketching the distribution of the rocks of their Azoic system, which comprises "for the most part gneiss, hornblende, chlorite, talcose and argillaceous slates, interstratified with beds of quartz, saccharoidal marble, and immense deposits of specular and magnetic oxide of iron" (p. 8), after describing the main area of these rocks to the northwest and north of the Felch Mountain range, say: "Another arm about

18 miles in length and 10 in breadth extends easterly into T. 42 and 43, R. 28" (p. 14). This east-and-west trending area corresponds in part with the Felch Mountain range, but also includes two adjacent troughs, one to the north of it, and the other to the south.

Subsequent to the above reports, nothing is known to have been published containing any matter concerning this iron-bearing area until 1869.

1869.

Credner, Hermann. Die vorsilurischen Gebilde der "oberen Halbinsel von Michigan" in Nord-Amerika. Zeits. der deutschen geol. Gesell., Vol. XXI, 1869, pp. 516-568. With map and three plates of sections.

In Credner's article we find a considerable advance in knowledge concerning the relations of the rocks of the Felch Mountain area. This advance is indicated by his general map (Pl. IX) and by his two profiles (fig. 3, Pl. IX, and fig. 1, Pl. X).

In profile No. 3, going from south to north, the granite is represented as overlain by quartzite, separated by a narrow interval from the marble, which in its turn is overlain by a great thickness of the ore formation. The dip is steep to the north. Unconformably upon the last two formations—the marble and the iron formation—there are caps of Potsdam sandstone, with the beds dipping flat to the north.

In fig. 1, Pl. X, the gneiss overlain by the quartzite, dipping steep to the north, are the only pre-Paleozoic rocks shown. The same profile shows the unconformable Potsdam, with Silurian dolomite resting conformably upon it.

In the text there is mention, with an illustration (fig. 5, Pl. IX), of the granite dike cutting across the iron formation in the upper course of the Sturgeon River. Beyond this no reference to the area under discussion occurs in the text.

1873.

Brooks, T. B. Iron-bearing rocks (economic). Geol. Surv. of Michigan, Vol. I, 1869-1873, New York, 1873, Part I. 319 pages. With maps.

In the year 1873 Maj. T. B. Brooks's very important study of the Michigan iron ranges appeared, and in it the Felch Mountain area for the first time is distinctly separated as "the North Iron Range" from the "South Iron Range" of the Menominee River iron region, both together, however, constituting the Menominee.

The north iron range, about 12 miles from the other in the south part of T. 42, Rs. 28, 29, and 30, is in places a prominent topographical feature. The capping of

horizontal sandstones, which has already been mentioned as characterizing the Menominee hills, gives a somewhat more even character to the crest lines, and in places produces a strikingly different profile (p. 72).

As stated by Major Brooks in a footnote on p. 157, the facts contained in the chapter on the Menominee iron region were derived largely from the surveys and explorations of Prof. R. Pumpelly and his assistant, Dr. H. Credner. The following passage is the most important statement concerning the Felch Mountain area, or the "North Range:"

> The north iron belt or range has a course nearly due east and west, and is all embraced, so far as known, in the south tier of sections of T. 42, Rs. 28, 29, and 30. The most easterly discovered exposure of ore, known as the Felch Mountain, is in the N. ½ of secs. 32 and 33, T. 42, R. 28. Traveling due west, fragments of iron ore are found in NE. ¼ of sec. 31, T. 42, R. 28; after which no absolute proof of the presence of iron is found (although it is probably continuous) until we reach sec. 31, T. 42, R. 29, where, in the center of the section, is an immense exposure of iron ore in an east-west ridge, which can be traced westerly halfway across section 36 of the next township. The natural exposure of ore on section 31 is larger than at any other point in the Menominee region, and the quality is as good, if not better, so far as can be judged by surface indications. Magnetic attractions and iron bowlders found farther west and southwest on this range prove its extension in that direction. Whether the westerly course continues, or whether it curves to the southwest, as seems probable from the position of the lower quartzite and local magnetic attractions in the northwest part of T. 41, R. 30, has not been determined. The latter hypothesis is most in accordance with the known facts, although the southeast dip of the quartzite on sections 17 and 18, observed by Dr. Credner, is not explained. If this hypothesis is true, the iron range should cross the Menominee somewhere in secs. 24 or 25, T. 41, R. 31, into Wisconsin. There can be little doubt but that the north and south belts belong to one geological horizon, hence somewhere come together (pp. 159-160).

A geological section through the north range on the line between Rs. 29 and 30, T. 42, is given, and is also represented as section CC′ on Atlas Plate IV. The succession from south to north is as follows:

Granite.
Quartzite.
Interval.
Marble.
Iron-ore formation.
Interval.
Marble.
Interval.
Granite-gneiss and hornblende and mica schist.

As represented in the section, the beds all dip toward the north at

high angles. In attempting to correlate these various beds with those of the south iron belt, Brooks experiences difficulty with the uppermost formation of granite-gneiss and schist. He says:

> The gneiss and granite outcrop above described may be almost regarded as a typical Laurentian rock in its appearance. If future investigations prove them to be Laurentian, a very troublesome structural problem would be presented here, as we would have Laurentian rocks conformably *overlying* beds unmistakably Huronian (p. 175).

As will be seen, this objection which Brooks had anticipated was raised by later workers in the area and was explained by Rominger.

The main points of Brooks's conclusions may briefly be summarized:

(1) The iron-bearing rocks of the Menominee region occur in two approximately parallel east-and-west belts (the north belt being the Felch Mountain range and the south belt the Menominee range), separated by a broad granite area which narrows toward the west by the convergence of the iron belts. The north-and-south belts were not traced into each other, but their probable connection was inferred from their bending toward each other and from the occurrence of rocks of the iron-bearing series west of the granite area. The equivalence in age of the two belts was inferred from the lithological and stratigraphical similarity exhibited by the great quartzite and marble formations, by the probable continuity above referred to, and by the similar relations of these formations to the basement granites.

(2) The iron-bearing formations of the Felch Mountain range were believed to occur at two horizons. That of Felch Mountain itself in sec. 32, T. 42 N., R. 28 W., was held to be a ferruginous phase of the lower quartzite. On the other hand, the exposures of sec. 31, T. 42 N., R. 29 W., were regarded as belonging to a horizon above the lower marble, and as the close equivalent of unimportant lean ores of the Menominee range.

(3) In geological structure the Felch Mountain area was held to be a northward-dipping monocline.

(4) As a consequence of this conception of the structure, Major Brooks supposed that there were two marble formations.

1880.

Brooks, T. B. The geology of the Menominee iron region, east of the center of Range 17 E., Oconto County, Wisconsin. Geology of Wisconsin, 1873–1879, Vol. III, published in 1880, Part VII, pages 429–599.

In Vol. III of the Geology of Wisconsin, published in this year, Brooks reiterates the views previously published in the Michigan reports. The only new material added is a table (p. 447) giving the estimated minimum thickness for the north belt as 5,200 feet.

1881.

ROMINGER, C. Geol. Survey of Michigan, Vol. IV, Part II, Menominee iron region. New York, 1881, pp. 155–241. With map.

This, the first of the reports of the geological survey of Michigan published while Dr. Rominger was in charge, contains a great number of details concerning explorations in the Felch Mountain range, as it is thus called (p. 194) for the first time in the chapter on the Menominee iron region. The iron-bearing belt along the Menominee River is referred to as the Quinnesee range.

Rominger criticises Brooks's position with reference to the age of the granite and gneiss along the northern border of the Felch Mountain range as follows:

Major Brooks declares the granites and the gneisses north of the Felch Mountain ore range as younger than the ore formation, which like them dips northward; but their superposition upon the ore formation is nowhere observable; on the contrary, the south side of the ore range exhibits in several places the direct superposition of the ore formation on the granite. This fact is known to Major Brooks, but he solves the dilemma by identifying the granites on the south side of the ore formation with the Laurentian; those on the north side, he claims, represent the youngest Huronian rocks. How he can do so I can not conceive, as the concerned granitic and gneissoid rocks north and south of the ore formation are so absolutely identical that no one who ever sees them can doubt for a moment the quality and age of these rocks. Moreover, this identification of the northern granite with the Upper Huronian, and of the southern with the Laurentian, implies another abnormity; groups of rocks, usually separated from each other by thousands of feet of intervening strata, are in this case thought to be in immediate superposition, which does sometimes occur, but not in coincidence with another improbability like the one stated in this instance (p. 207).

1887.

IRVING, R. D. Is there a Huronian group? Am. Jour. Sci., Vol. XXXIV, 1887, pp. 204–263, 365–374. Read before the National Academy of Sciences April 22, 1887.

In discussing this question, Professor Irving takes occasion to refer to the structure of the Felch Mountain range:

In the case of the Felch Mountain belt, which does not exceed a mile in width, all of the strata are described by Dr. Rominger as dipping at a high angle to the

northward; and in crossing the belt from the south to the north, after passing the middle, one traverses a repetition of the belts crossed farther south, but in an inverted order. It would seem that we have to do here with a case of a synclinal, whose sides are folded close together (p. 256).

The relations of the Felch Mountain range to the rocks of the Menominee River and the Marquette district are shown on a profile. The facts are mentioned as having been derived from an unpublished manuscript report (1881 to 1884) of Rominger to the Michigan geological survey.[1]

1888.

IRVING, R. D. On the classification of the early Cambrian and pre-Cambrian formations. Seventh Ann. Rept. U. S. Geol. Survey, for 1885-86, Washington, 1888, pp. 365-454.

In this article the statements made above are repeated (p. 435).

1891.

VAN HISE, C. R. An attempt to harmonize some apparently conflicting views of Lake Superior stratigraphy. Am. Jour. Sci., Vol. XLI, 1892, pp. 117-137.

The author of this paper, after discussing the significance of the various unconformities observed and after dividing the rocks of the Marquette district into a Fundamental Complex and a Lower and an Upper series, attempts to correlate the rocks of the Menominee region with these divisions.

Passing now to the Menominee and Felch Mountain districts, our information is less exact. It is, however, clear that in both of these areas we have the Fundamental Complex—that is, the granites and the gneisses associated with crystalline schists having the usual "eruptive contacts"—the equivalence in every respect of Lawson's combined Laurentian and Coutchiching period. Above this complex, Professor Pumpelly, with whom this whole subject has been discussed, and who has great familiarity with the entire Lake Superior region, suggests as exceedingly probable that in the Felch Mountain iron-bearing series only the equivalent of the Lower Marquette occurs, the Upper series, if it once existed, having been removed by erosion (p. 133).

1892.

VAN HISE, C. R. Correlation papers—Archean and Algonkian. Bull. U. S. Geol. Survey, No. 86, Washington, 1882, pp. 549.

In a summary of the literature on the Lake Superior region, the statement quoted above is incorporated without change (p. 190).

[1] Published in 1895, Vol. V.

1893.

WADSWORTH, M. E. Report of the State geologist for 1891–92. State Board of Geol. Surv. for the years 1891 and 1892, Lansing, 1893, pp. 61–73. Dated October 17, 1892.

In this brief report Dr. Wadsworth calls attention to the granite which is intrusive into the sedimentary series in the Felch Mountain area.

In the Menominee region, especially in the Felch Mountain district, these granite dikes are well exposed. Here they are seen not only to cut the gneiss, but to penetrate the Republic or iron formation. Mr. Wright, in 1885, pointed out one of these dikes cutting the iron series near the Metropolitan mine, on sec. 32, T. 42, R. 28 W. (p. 101).

He includes the Felch Mountain dolerites (p. 104) in his Republic formation, and correlates this formation with Van Hise's Lower Marquette series.

1895.

ROMINGER, C. Geological report on the Upper Peninsula of Michigan, exhibiting the progress of work from 1881 to 1884. Iron and copper regions: Geol. Surv. of Michigan, Vol. V, Lansing, 1895, pp. 1–94.

Chronologically, this is one of the latest reports upon the Upper Peninsula of Michigan, yet in justice to the author it should be considered as having priority over any articles published since Irving's, in 1887, to which reference has already been made, as in that article Irving made use of the observations recorded in the manuscript of this report, giving Rominger full credit for them. In Rominger's report, in the chapter on the Granitic Group, the granite dike cutting the iron-bearing formation in the Felch Mountain range is described (p. 7). He also describes a wedge-like intrusion into the highly contorted strata in sec. 33, T. 42 N., R. 28 W., as follows:

We have here evidently before us a series of strata plicated into a synclinal and another anticlinal fold, the latter ruptured by an intruding granite mass, which rock is there the general surface rock and comes on the south end of the exposure in contact with the uppermost ferruginous strata of the overtilted anticlinal fold (p. 8).

The portion of the chapter on the iron-ore group which deals with the Menominee region is devoted to the Felch Mountain range and to outlying prospects as far north as Michigamme Mountain. The description of the Felch Mountain area is in great part a condensation of earlier scattered observations. The strata are given as dipping high to the north and consisting of the following succession:

The underlying rock of the iron formation is always formed of crystalline rocks, granite or diorite. The lowest strata are generally heavy light-colored quartzite

beds, with interlaminated thinner ledges and schistose seams, amounting to considerable thickness.

Above this belt an equally large succession of well-laminated, even-bedded, often fissile, slate-like micaceous quartz-schists follow, which have a silvery luster. Next above them comes a series of micaceous argillites, amounting to a belt even larger than the former, which varies greatly in shades of color, firmness of grain, etc.; some layers are whitish, others gray or bluish and greenish, but the greatest portion of them is intensely red colored by hematitic pigment. A part is a fatty, impalpably fine mass of silky or also pearly luster, according to the size of the mica shales incorporated with them. Another part is rough and gritty from the prevalence of arenaceous constituents.

At this horizon and rather in the lower part of it occur locally large bodies of crystalline limestone ledges, some snowy white like Italian marble, but of coarser crystalline grain and intermingled with radiating clusters of asbestine fibers and larger prismatic crystals of colorless tremolite, which sometimes forms larger concretionary seams in the lime rock, and are then intimately associated with crystal masses of sahlite, one mineral penetrating the other in a manner which suggests either a process of paramorphosis in progress, changing the sahlite into tremolite, or the original conditions, when the calcareous material combined with the silica by a slight modification, induced simultaneously the crystallization of the almost identical chemical combinations in one and the other form; which latter suggestion is more sustained by the actual condition of the mingled minerals than the first, as some of the crystals of both minerals tightly grown together are so perfect in form peculiar to each and so sharply defined that they must be considered as crystal individuals which formed side by side and altogether independent of one another. In other localities where such crystalline limestone belts occur, the tremolite is only sparingly intermingled, but in its place colorless mica scales of nacreous luster are plentifully disseminated.

In the place of marble-like limestone, sometimes also ordinary lime rock of dull aspect with conchoidal fracture, and variously tinged, occurs; it is then usually full of flinty siliceous seams, resembling the limestones of the Quinnesec range; the quartzose seams, locally even, prevail over the calcareous. Incumbent on the above-mentioned micaceous argellites succeeds a belt, about 800 feet in width, composed of thinly laminated, banded, ferruginous, quartzite ledges of dark purplish tints or having a metallic luster from intermixture of specular ore granules. The banded portions are formed of an alternation of narrow seams of specular ore with siliceous seams not so richly impregnated with the oxide. Other strata in the succession are porous cherty rocks charged with ochreous yellow or brown oxide of iron and inclosing pockets of the limonitic ore. Also blood-red argillitic seams occur in the succession, and with them sometimes pockets of soft crumbly hematite ore.

Within the first-mentioned banded alternation of narrow ore seams with quartz seams, larger deposits of specular ore in slaty or in compact granular, or also in the soft friable condition of the so-called blue ore of the Quinnesec mines occur, which constitute the principal storage of ore sought for by the miner, besides the hematitic and limonitic deposits mentioned before. The first impression of every observer examining this above-described rock series will induce him to consider it as an ascending succession, as the layers follow one another in apparent conformity; but in some localites, after having crossed this succession so far, if we proceed farther in the same

direction, we intersect the same series again in an inverted order, but retaining the same dip, until we have reached again a large belt of compact quartzite ledges in close contiguity with granite or also diorite, as it may happen, which latter rocks then form the surface rock of large areas on the north side of the Felch Mountain ore formation (p. 33).

The only satisfactory explanation which I can give of this repetition of the rock beds in an inverted order is the suggestion of a folding of the beds and the overturn of the fold by a pressure acting principally from the north side. If this is the case, we would have to consider the light-colored quartzite next to the granite as the most recent deposits and the dark, ore-bearing, banded quartz beds as the oldest, which would bring the structure of the Felch Mountain ore formation in perfect harmony with that of the Quinnesec ore range (p. 34).

SECTION II. GENERAL SKETCH OF THE GEOLOGY.

The rocks of the Felch Mountain range extend from the Archean to the early Paleozoic. The Paleozoic is represented by the Lake Superior sandstone, of supposed Upper Cambrian age, and the overlying Calciferous limestone. These formations were originally laid down over the upturned edges of the older rocks in flat sheets or with low initial dips, and have not since suffered relative displacement to any notable degree. As has already been stated, subsequent erosion has to a great extent removed this overlying blanket and laid bare the older rocks, except for the covering of recent glacial deposits. The Cambrian sandstone, and to a less extent the Calciferous limestone, still, however, occupy considerable outlying areas, detached from one another throughout most of the district, but gradually coalescing beyond the eastern end, where they completely cover the older rocks and limit all further geological study of these in that direction.

The Paleozoic rocks will not be considered further at present. On the detailed Felch Mountain map (Pl. XLIX) their known outcrops are represented by appropriate symbols, but except in the larger areas, where they so completely conceal the older rocks that the distribution of these can not be determined, they are assumed not to be continuous, and to be nonexistent, and in this respect stand upon the same footing as the Pleistocene glacial covering.

The Archean, which is here made up of granites, granitic gneisses, and various kinds of crystalline schists, is the basement group of the region. The areas in which these rocks are now exposed at the surface represent the cores of the larger arches which were constructed over the whole region by the early manifestations of mountain-building activity, and subsequently

truncated by the deep Cambrian denudation. Our studies have dealt with the Archean only in narrow marginal zones, and have included little more than the location of its outer boundaries, except when it was necessary to go deeper in order to complete the work over a full section. Consequently no attempt at classification can be made upon the map.

The rocks, chiefly of sedimentary origin, which are intermediate in age between the Archean below and the Paleozoic above, and therefore fall within the system to which the name Algonkian has been given by this Survey, occupy a narrow strip nowhere more than a mile and a half and usually less than a mile wide, which as a whole runs almost exactly east and west for a distance of over 13 miles. This strip constitutes the Felch Mountain range. On the north and south it is bordered by the older Archean. The lowest member of the Algonkian occupies parallel zones next to the Archean both on the north and south, and is succeeded toward the interior of the strip by the younger members. While the general structure, therefore, is synclinal, a single fold of simple type has nowhere been found to occupy the whole cross section of the Algonkian formations, but usually two or more synclines occur, separated by anticlines, which may have different degrees and directions of pitch and different strikes, or may be sunk to different depths, and complicated besides both by subordinate folds and by faults.

Among the Algonkian rocks we distinguish two main divisions or series, which are probably separated from each other by an unconformity. Owing mainly to the peculiar lithological and weak physical character of the younger of these two series, actual contacts between them have not been found, and the evidence of unconformability consequently consists not so much in observed discordance of structure as in an inferred discordance based upon their relative surface distribution. This evidence will be fully stated hereafter.

In the lower of these two series are included four formations which clearly appear to be identical in lithological character and order of superposition with the four formations that, so far as is known, make up the lower iron-bearing series along the Menominee River. These are, reckoning from the base upward, (1) the Sturgeon quartzite, (2) the Randville dolomite, (3) the Mansfield schists, (4) the Groveland iron formation.

Above this series follows the younger series, which lithologically and in

its areal relations is very incompletely known. It includes mica-schists, ferruginous schists, and thin interbedded ferruginous quartzites. These rocks, which from our imperfect knowledge must for the present be grouped as a single formation, are believed to have been deposited contemporaneously with the somewhat similar rocks that occur in the Menominee area, at Iron Mountain, but are most extensively exposed west of the Menominee River, and especially in the Commonwealth and Florence district in Wisconsin.

SECTION III. THE ARCHEAN.

The Archean occurs in the Felch Mountain district in two belts, which limit the Algonkian rocks on the north and on the south. The northern belt for the most part does not fall within the limits of the detail map (Pl. XLIX). It occupies a triangular corner in secs. 34 and 35, T. 42 N., R. 30 W., at the extreme western end of the area surveyed, and even in these it has not been directly observed, but its presence is inferred from outcrops in the adjoining sections west and north and from the observed strikes in the overlying Algonkian formations. For the next 11 miles east its southern boundary lies in the tier of sections next north of those mapped in detail and probably always less than a mile away. This boundary is therefore not very accurately drawn, as only enough outcrops were visited to permit its position to be fixed in a general way. Our work first touches the southern area of the Archean, which is much better known on the west in secs. 3 and 2, T. 41 N., R. 30 W., a short distance south of the township line. Thence for 3 miles eastward the boundary follows the township line, and in sec. 31, T. 42 N., R. 29 W., crosses it with a trend somewhat north of east. From the west line of sec. 31 to the east line of sec. 36, T. 42 N., R. 29 W., the Archean occupies the southern third of the south tier of sections. Thence for a mile and a half it bends northeast, and in sec. 32, T. 42 N., R. 28 W., reaches its farthest north in the center of the section. From this point the boundary runs southeast, with a sinuous embayment to the south, and passes outside the limits of the map a little north of the southeast corner of section 33.

Throughout the Felch Mountain range the southern Archean is much better exposed than any of the other terranes. In the western portion of the range, where hardly more than the contact zone falls within our limits,

outcrops are not especially numerous; but in the six eastern sections, which include a belt from a quarter to half a mile wide, a very considerable portion of the surface is bare rock. This exceptional degree of exposure has been brought about by the forest fires, which, by loosening the thin soil and destroying the protecting cover of vegetation, have facilitated its removal from the steep-sided knobs that are such characteristic features of the Archean topography.

TOPOGRAPHY.

The Archean areas, particularly the southern, are distinguished by a characteristic rough topography. The surface is exceedingly uneven on rather a small scale, and has already been described as consisting of hummocky elevations alternating with bowl-shaped depressions. Both hummocks and bowls are elongated in an east-and-west direction, in accordance with the prevalent gneissic foliation.

While the surface is thus so full of small details that an adequate delineation of it is the despair of the topographer, the actual relief is insignificant. To men bred on the flat plains of the lower lakes, as were most of the early surveyors and explorers, it may naturally have appeared mountainous, since roughness is a quality particularly noticeable in a wilderness like this, that can be traveled only on foot. But from a broader point of view the irregularities are almost wholly lost. The higher summits in the same neighborhood rise to within a few feet of each other. The distant sky line is even in all directions. There is, however, a gentle ascent from east to west, quite imperceptible on the ground, and made evident only by the general course of the streams or by leveling.

Along the contacts between the Archean and Algonkian systems there usually but not always exists a topographical depression, occupied by swamp or streams. North of the southern Archean mass this depression is a well-marked linear valley, extending with some interruption from sec. 33, T. 42 N., R. 28 W., on the east, for 6 miles west to sec. 33, T. 42 N., R. 29 W. For 2 miles in the middle of this stretch the valley is occupied by the Sturgeon River; thence west for 2 miles by a small feeder of the Sturgeon, while the eastern third holds swamp with ill-defined drainage. On the south the Archean boundary of this valley generally rises with

steep slopes, which are frequently escarpment-like in character, and for short distances present smooth faces to the valley. In sec. 33, T. 42 N., R. 28 W., the mural face which runs southeast across the eastern half of the section with the regularity of a ruled line is a true fault scarp. Toward the western end of this valley, in sec. 32, T. 42 N., R. 29 W., the floor gradually rises and the swamp area broadens, penetrating the Archean in a network of thicker and thicker mesh about the higher hummocks, until these are finally overtopped.

PETROGRAPHICAL CHARACTERS.

The rocks of the Archean areas may be divided into four quite distinct types, namely: (1) Granites or granitic gneisses, (2) gneisses with banding or distinct lamination, (3) mica-schists, and (4) hornblende-gneisses or amphibolites. Between the first two divisions there is an extremely close mineralogical and chemical likeness, while in these respects the fourth division stands against all the others in strong contrast.

(1) The granites of the first division are, as seen in the field or in the hand specimen, holocrystalline rocks of fine to medium grain, in which the eye can readily distinguish the presence of quartz, pink feldspar, muscovite, and biotite. In color they are prevailingly of pink or reddish tints of light shades. Structurally, they frequently appear in small areas to be entirely massive, but even in the most massive occurrences the hammer can usually part them along roughly parallel surfaces which glisten with spangles of mica, indicating a certain degree of alignment in these constituents. Generally, however, a rude foliation is more or less distinctly visible, and is sometimes exceedingly well developed, even to the point of fissility. It is always apparently due to the parallel arrangement of the micas, which are more abundant as the foliation becomes more distinct.

The field relations show that the massive and more or less foliated varieties of this division are closely bound together by indistinguishable gradations and, indeed, often constitute a visibly integral mass. The usual arrangement of the micas is not parallel to a surface but parallel to a line which is generally inclined to the horizon at angles varying between 10° and 35°. A hand specimen when turned about the direction of foliation as

an axis, shows a parallel arrangement of the micas on all sides, and a continuous glisten follows the revolution; while on a surface at right angles to this direction the micas are not parallel and wind about the other constituents indifferently. In the more fissile varieties the outcrops often have a rough, channeled surface, suggestive of the surfaces familiar in closely crenulated mica-schists, or on the corrugated walls of a fault. Similar corrugated surfaces frequently part more massive from more fissile parts of the same outcrop.

Under the microscope the essential constituents of the granites and granitic gneiss are seen to be quartz, orthoclase, microcline, plagioclase, biotite, and muscovite, with the iron ores, titanite, and occasionally apatite and zircon as accessories. In the massive phases the general relations of these minerals to one another, and their order of crystallization, in no respect differ from those of igneous granite. The quartz, which is the last mineral to form, contains numerous fluid and gas inclusions, the former often with a moving bubble. Of the feldspars microcline is much the most common, then plagioclase, while orthoclase is generally comparatively rare, although sometimes it is more abundant than the microcline. The plagioclase, from its relief and extinction angles, is probably not lower in the scale than oligoclase. The orthoclase is usually clouded with alteration products, and sometimes the dull interior is surrounded with a narrow unattacked rim. Both micas are always present as original minerals, and on the whole biotite is the more abundant. They occur in small stout crystals, often as inclusions in the quartz and feldspars. Magnetite is rare, but occurs in idiomorphic forms in the later constituents, as do also minute crystals of zircon and apatite. Thin sections of even the most massive-looking specimens invariably show the effects of pressure in the undulatory extinction of the quartz and in the bending and occasional fracture of the feldspar.

In the foliated varieties with which these massive varieties are closely associated the effects of mechanical stresses are the striking microscopic phenomena. The constituent minerals are essentially the same as in the massive phases, but the micas are relatively more abundant. The quartz and feldspar individuals are fractured and strained, and occur in irregular cores separated by anastomosing zones of a fine quartz-feldspar mosaic. In these last, new micas, in long curving individuals and clusters, have been developed in great numbers.

The following analyses give the chemical composition of these granites:

Analyses of granites.

[By Dr. H. N. Stokes, U. S. Geol. Survey.]

	1.[1]	2.[2]	3.[2]
SiO_2	76.10	72.17	69.69
TiO_2	.07	.27	.29
CO_2	None.		
P_2O_5	.02		
Al_2O_3	12.95	14.44[3]	15.64[3]
Cr_2O_3	None.		
Fe_2O_3	.65	1.02	.90
FeO	.09	.99	1.62
MnO	Trace.		
NiO	None.		
CaO	.12	.69	1.22
MgO	.14	.70	.66
K_2O	6.50	4.84	5.30
Na_2O	2.36	3.65	3.34
H_2O at 110°	.17		
H_2O above 110°	.48		
Total	99.65		

[1] Ba, Sr, Li, Cl, S, SO_3 were not looked for. [2] Water not determined. [3] Includes P_2O_5.

No. 1. Specimen 34677, Lake Superior Division, U. S. Geol. Surv., 1,935 N., 1,040 W., sec. 2, T. 41 N., R. 30 W., Upper Peninsula of Michigan.

No. 2. Specimen 34828, Lake Superior Division, U. S. Geol. Surv., 300 N., 1,850 W., sec. 36, T. 42 N., R. 29 W., Upper Peninsula of Michigan.

No. 3. Specimen 36081, Lake Superior Division, U. S. Geol. Surv., 15 N., 1,025 W., sec. 31, T. 42 N. R. 28 W., Upper Peninsula of Michigan.

No. 1, which is rather low in alumina, iron, and lime, is a granitic gneiss in which the abundant secondary mica, which has grown in long curving plates in nearly parallel zones of granulation, is wholly muscovite. Nos. 2 and 3 are fine- and coarse-grained pink granites, which show comparatively little crushing and development of secondary minerals in thin section.

The rocks of this division therefore have the chemical composition as well as the physical and petrographical characters of igneous granites. The positive proof of igneous origin, however—actual injection into older rocks—we have not found. Irruptive contacts may possibly exist, and may have escaped us, since neither the Archean as a whole nor its internal relations were the objects of especially rigid scrutiny. Igneous granites of Algonkian or later age ought to be found within the Archean areas, for several granite dikes are known to penetrate various members of this overlying series. Whether the known granites within the Archean are really lower-lying and larger masses with which such dikes are genetically con-

nected is not known, but the possibility must be admitted. The banded gneisses are often so faintly foliated and resemble the granites so closely in color and grain that the distinction can be made with only the microscope, and igneous contacts between them might easily be overlooked. It is certain, however, that if the granites have been injected into the banded gneisses it has not been in the form of narrow dikes, and the fact remains that no case of an igneous contact is recorded in our notes.

The gneissic members of this division are merely crushed granites, and owe their foliation partly to the crushing and partly to the growth of fresh mica in the fractured zones. They differ from the banded gneisses in furnishing both field and microscopic proof of the way in which the foliation was formed and of the rocks from which they were derived.

(2) The banded gneisses of the second group have essentially the same mineral composition as the granitic gneisses of the first. They are distinguished by the eye mainly by the fact that the component minerals occur in more or less distinct layers, from a fraction of an inch upward in thickness. The lamination, which only rarely is very regular, seems to be caused in most if not in all cases by the alternation of darker layers, which are relatively rich in biotite, with lighter layers, which are comparatively and sometimes wholly free from it. The light layers are almost always coarser in texture than the darker, and frequently are coarsely pegmatitic. The individual bands are not indefinitely persistent, but wedge out to knife-edges. The banding is sometimes so indefinite as to be lost in the hand specimen, the large surface of an outcrop being necessary to bring out the slight differences in shade. In color these rocks are light gray, dull white, or pink. The banding shows great variations in angle of dip, but the strike is usually fairly constant within a few degrees of east and west. In a few localities distinct contortion was observed in the gneissic banding and pitching folds. The lamination of these gneisses is, so far as observed, of the plane-parallel type. The bands are thoroughly welded together, and as a rule, the rock breaks indifferently across them.

Under the microscope the composition of these rocks does not differ from that of the granitic rocks of the first division. The structural characters, however, are in strong contrast. Even in those specimens which possess the most indistinct foliation all the minerals are elongated in a common direction. While the individual grains in most cases show more or less strain and are frequently fractured, their mutual boundaries are usually sharp and clear, and it is evident that the forms are not the direct

result of the pressure that has affected their optical properties. The evidence is quite clear that the minerals now present have crystallized in parallel elongated forms, and it is to this they owe their prevalent lamination even when the color banding is indistinct or wanting.

Subsequent to the time of crystallization they have been exposed to the action of great stresses, which not only have left a record in the strains now frequently perceptible in the minerals of the early crystallization, but also in many cases have produced roughly parallel fractures and fracture zones sometimes coinciding with and sometimes oblique to the early lamination. In these zones coarse micas have grown, reenforcing the old lamination when parallel to it, and when oblique producing a less regular secondary foliation, which is entirely analogous and probably contemporaneous with the foliation of the crushed granites.

The following analyses of these gneisses are interesting as showing their striking chemical relationship to the granites (analyses of which are given on p. 389), with which they are intimately associated:

Analyses of gneiss.

[By Dr. H. N. Stokes, U. S. Geol. Survey.]

	1.[1]	2.[2]	3.[2]
SiO_2	74.37	71.79	74.63
TiO_2	.07	.35	.09
CO_2	None.		
P_2O_5	.01		
Al_2O_3	13.34	14.79[3]	13.95[3]
Cr_2O_3			
Fe_2O_3	.92	1.10	.35
FeO	.21	1.09	.32
MnO	Trace.		
NiO			
CaO	.50	1.11	1.08
MgO	.27	.71	.22
K_2O	6.70	3.79	6.73
Na_2O	2.50	4.29	2.55
H_2O at 110°	.12		
H_2O above 110°	.44		
Total	99.45		

[1] Ba, Sr, Li, Cl, S, SO_3 were not looked for. [2] Water not determined. [3] Includes P_2O_5.

No. 1. Specimen 34826, Lake Superior Division, U. S. Geol. Surv., 240 N., 1,250 W., sec. 35, T. 42 N., R. 29 W., Upper Peninsula of Michigan.

No. 2. Specimen 36058, Lake Superior Division, U. S. Geol. Surv., 325 N., 1,225 W., sec. 36, T. 42 N., R. 29 W., Upper Peninsula of Michigan.

No. 3. Specimen 36080, Lake Superior Division, U. S. Geol. Surv., 15 N., 1,025 W., sec. 31, T. 42 N., R. 28 W., Upper Peninsula of Michigan.

(3) The mica-schists are not widely distributed in the portion of the Archean areas included in the Felch Mountain map. They are well represented in the northern Archean area beyond the limit of the area mapped, but within this limit they are known only in secs. 34 and 35, T. 42 N., R. 29 W., where an overthrust fault brings them into successive contact with the Randville dolomite and Sturgeon quartzite for a distance of three-fourths of a mile. An excellent section, which includes the faulted contact with the dolomite, is exposed along the Sturgeon River below the dam in the northern portion of section 35. Though so feebly represented, they possess an unusual interest both in their field relations and in their microscopic characters.

The mica-schists when fresh are dark gray, rather soft rocks, of fine to medium grain, with a generally well-developed schistose structure. The most noticeable constituent, in spite of the dark color, is muscovite, which occurs in pearly flakes of large size plentifully sprinkled along the cleavage surfaces, and is especially characteristic of thin seams, which are much more fissile than the rest of the rock and part it into parallel bands of much regularity. Biotite, however, is the more abundant mica, although in smaller and less conspicuous plates, and to it the dark color of the rock is due. Quartz and sometimes feldspar may also be recognized.

These rocks offer little resistance to the weather. The biotite gives up its iron with great ease, staining the outcrop a dull red. The final product is a slightly coherent ferruginous mixture in which the large muscovite plates alone are recognizable. At a less advanced stage of weathering the alternation of layers more rich in biotite produces color banding in reds and grays.

The mica-schists contain many intruded dikes and sheets of flesh-colored pegmatite and also of amphibolite, both of which are generally parallel to the foliation. The pegmatites are typical "schrift-granits," the feldspar being microcline. Both pegmatites and amphibolites show ragged and intrusive contacts with the schists when these are examined in detail. Both also are foliated.

Under the microscope the mica-schists are thoroughly crystalline aggregates of quartz, biotite, and muscovite, always with more or less microcline. Magnetite is always present as a primary mineral, and hematite or some hydrous oxide of iron between hematite and limonite is very abundant in the zone of weathering. Besides these, tourmaline is an abundant accessory in some slides, and apatite, zircon, titanite, pyrite, and chlorite also commonly occur.

Quartz occurs in small and often partly rounded areas, some of which have a very clastic appearance. Except as stated below, it is generally free from inclusions of the micas, which surround and terminate against it in such a way as to indicate that it crystallized the earlier. It is often crowded with fluid and gas inclusions, and an occasional grain bristles with radiating clusters of rutile needles. Minute crystals of magnetite are also frequently inclosed. The inclusions of all kinds are frequently grouped in roughly oval areas near the centers of the grains, while between the nuclei and the wandering perimeters the quartz is relatively free from inclusions.

Biotite, varying in color from dark brown to light yellowish green, is the predominant mica. It occurs in irregular plates, generally much larger than the quartz; the great abundance and uniform alignment of these plates produce the schistose structure. As already stated, it includes and is therefore younger than the quartz generally, but it is also found, though rarely and always in very minute plates, included in the small quartz grains which are so abundant in the fresh microclines. The latter occurrences belong to an earlier generation than that of the larger biotites. The chief interest attaching to the biotite is in its alteration under the attack of the weather. The iron separates out along the cleavages in little spheroidal drops and flattened plates, which are red and translucent, but not quite of the deep color of hematite. Doubtless they contain some water, and are possibly close to göthite in composition. Between the red globules the biotite substance becomes paler, its pleochroism diminishes, and double refraction increases, and finally, in a slide containing no basal sections, it can not be distinguished from muscovite. The separated ferric oxide remains in the mica, and while the rock remains firm does not travel and stain the other constituents. In these stages the slide contains a very faintly colored bleached biotite, which is sprinkled through and through with the little dots of bright red iron ore.

Muscovite is not very abundant. It is sometimes intergrown with the large biotites, and occurs under similar conditions, but it chiefly comes in little ragged inclusions in the secondary microcline. In the form of aggregates of sericite it composes the macroscopically conspicuous pearly micas, and also is an abundant constituent, and sometimes the only representative, of the partly absorbed and older feldspars included in the microcline.

Microcline is always a secondary mineral, and is present in variable

amounts in different sections. It incloses quartz, the micas, magnetite, and an older feldspar. These inclosures are usually small; they often lie in parallel alignment in the same and adjoining microclines, and the lines in which they are disposed sometimes bend, apparently indicating that the original rock was minutely puckered. The inclosed quartz sometimes incloses smaller flakes of biotite and muscovite, as well as magnetite and rutile needles. The inclosures in the little grains of quartz are frequently concentrated in the centers, as in the case of some of the quartzes outside the microclines, as described above. The microcline sometimes occurs in a few scattered grains; sometimes with its inclusions it makes up almost the whole rock. In its manner of occurrence, its inclusions, and the way in which these are disposed within it, it is strikingly like the secondary albite of the Hoosac schists of western Massachusetts, described by Prof. J. E. Wolff.[1]

The microclines are distinctly elongated in a direction parallel to the foliation, to which they thus contribute. In a few cases the elongation is parallel to a line, and does not appear in thin sections cut normal to this direction. But in most cases the crystals are flattened parallel to a plane. These forms are those of crystallization; except along the secondary fracture planes the microline is entirely free from breaking or granulation.

The following is a complete analysis of a representative specimen of the mica-schist:

Analysis of mica-schist.

[By Dr. H. S. Stokes, U. S. Geol. Survey.]

	1.		1.
SiO_2	64.71	CaO	0.08
TiO_2	.72	MgO	2.97
CO_2	None.	K_2O	5.63
P_2O_5	.02	Na_2O	.11
Al_2O_3	16.43	H_2O at 110°	.31
Fe_2O_3	1.83	H_2O above 110°	2.79
FeO	3.84	Total	99.44
MnO	Trace.		

No. 1. Specimen 34822, Lake Superior Division, U. S. Geol. Surv., 1900 N., 1310 W., sec. 35, T. 42 N., R. 29 W., Upper Peninsula of Michigan.

[1] Mon. U. S. Geol. Survey, Vol. XXIII, pp. 59–63.

In its low silica and lime, and high iron and magnesia, this rock differs in important particulars from the granites, to which in its mineral composition it is allied. In these respects, as well as in the great excess of potash over soda, it closely approximates the composition of certain clay slates.[1]

The original character of the mica-schists is indeterminate. They may be altered sediments, as the chemical analysis indicates, but if so they no longer contain any material which can be proved to be in its original form, and in view of the complete recrystallization, for which the evidence is clear and striking, this could not be expected. Their mineralogical relationship and close association with the granites and gneisses is perhaps a reason for regarding them as autoclastic rocks, derived from originally massive granites by dynamic metamorphism. If this be true, then the crust movements which crushed the parent granite belong to pre-Algonkian time, for the later stresses which folded and brought the schists into faulted contact with the Randville and Sturgeon formations found them with a parallel foliation which it bent and crumpled, and no period of great stress earlier than this is known in Algonkian time. The complete recrystallization may be referred with probability to the period of quiescence following the faulting and folding, during which also occurred the recomposition of the older Algonkian formations.

(4) The amphibolites or hornblende-gneisses are widely and abundantly represented in the Archean. Macroscopically they are black or dark-green rocks of medium to fairly coarse grain, the fresh fractures of which glisten with the cleavage surfaces of hornblende, which is much the most abundant and often the only recognizable constituent. They are universally foliated parallel to the foliation of the associated gneisses, and exhibit, but in a more marked degree, the same varieties of structure. The foliation is easily recognized by the eye as due to the parallel arrangement of the hornblende prisms. Depending mainly upon the position of the hornblendes relative to the other constituents, the structure is either of the plane-parallel or linear-parallel type, the latter often superbly developed.

The essential constituents of these rocks are common green hornblende, plagioclase, biotite, and quartz. The structure is thoroughly crys-

[1] See analyses quoted by Kemp, Handbook of Rocks, p. 107, nos. 4 and 5.

talline. The hornblende occurs in long prisms 3 to 10 mm. in length, which lie close together, and inclose, partially surround, and abut against smaller angular grains of plagioclase. The plagioclase is quite unstrained and is usually fresh and clear, and entirely without crystal boundaries. Brown biotite is universally present in small amount, in long plates parallel with the foliation. It does not seem to be an alteration product from the hornblende. Quartz is the least abundant constituent. It is crowded with fluid cavities and needles of rutile, and often incloses minute crystals of hornblende. The plagioclase, from its high extinction angles and alteration products, is evidently basic. A little magnetite is present, but titanite has not been observed.

The structural features are well brought out in thin section In the linear-parallel type the hornblendes all lie with their crystallographic axes parallel to a line. A thin section parallel to the foliation cuts essentially all in the zone of the prism or near it; one across the foliation gives only sections across the prism. The grains of plagioclase are generally elongated without strain. Their outlines are most irregular and quite independent of the twinning lamellæ. Their general appearance is that which would be presented if numerous crushed contiguous grains had united by some process of annealing or absorption to form the new individuals. In the plane-parallel type the only difference is that the hornblende prisms have grown parallel to a plane, in which, however, they may have any orientation An indistinct banding is also often observable in this type, caused by a partial grouping of the light and dark constituents in parallel layers. The order of crystallization seems to have been plagioclase first, but nearly contemporaneous with the hornblende and biotite, and the quartz last.

The amphibolites occur in comparatively narrow bands of indefinite length in the granites and gneisses. The width usually does not exceed 8 to 10 feet, and their dip is always at high angles. The boundaries are invariably sharp, and frequently cut the foliation of the amphibolite within and of the gneisses without somewhat obliquely. There is a general uniformity of grain throughout the width; the wider bands are not coarser than the narrower.

The following complete analysis shows the chemical character of a representative specimen of amphibolite:

Analysis of amphibolite.

[By Dr. H. N. Stokes, U. S. Geol. Survey.]

	1.[1]		1.[1]
SiO_2	50.36	NiO	
TiO_2	1.77	CaO	7.85
CO_2	None.	MgO	5.55
P_2O_5	.20	K_2O	1.14
Al_2O_3	13.26	Na_2O	2.11
Cr_2O_3		H_2O at 110°	.16
Fe_2O_3	6.30	H_2O above 110°	1.55
FeO	9.34	Total	99.59
MnO	Trace.		

[1] Ba, Sr, Li, Cl, S, SO_3 were not looked for.

No. 1. Specimen 36407, Lake Superior Division, U. S. Geol. Survey, 1140 N., 1000 W., sec. 32, T. 42 N., R. 28 W., Upper Peninsula of Michigan.

From this analysis it appears that the rock has essentially the composition of diabase or basalt. The composition of the amphibolites, as shown by the above analysis, and their field relations leave little room for doubt that they are old dikes of basic rock.

Their present crystallization is of course not that due to original cooling, since among other reasons it bears no relation either to their thickness or to distance from the walls. The evidence of complete recrystallization in place after consolidation which they thus afford, and the unquestionable community of origin between their foliation and that of the gneisses, are significant facts in the metamorphic history of the Archean of this district.

It is for this reason that they are described with the Archean and not with the intrusives. Whether they are really Archean intrusions and not of Algonkian age can not, perhaps, be known with certainty. Basic rocks having approximately the same composition are known to have penetrated the Algonkian, but they have not undergone the same recrystallization. These last besides have their known analogues, equally unmetamorphic in the Archean itself. For these reasons it seems probable that the amphibolites were intruded into the Archean before the Algonkian rocks of this district were deposited.

SECTION IV. THE STURGEON QUARTZITE.

The lowest member of the Algonkian in the Felch Mountain range is a formation consisting mainly, but not exclusively, of coarse vitreous quartzite. Typical exposures of this formation, as well as one of the rare contacts between it and the underlying Archean, occur along the Sturgeon River, and it is therefore named the "Sturgeon Quartzite."

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The Sturgeon formation, next to the Randville dolomite, is the most widespread member of the Algonkian series in the Felch Mountain range. Its general distribution throughout the area mapped is in two parallel zones, of varying width, immediately adjoining the northern and southern Archean, except when displaced from this position for relatively short distances by faults. These zones extend east and west for the whole length of the range. Their surface width varies with the complexity of the structure and the depth of erosion. In part of sec. 35, T. 42 N., R. 29 W., the higher formations have been entirely removed, and the two zones come together, leaving the quartzite as the only Algonkian rock at the present surface.

On the whole the Sturgeon formation is fairly well but very unevenly exposed. Beginning at the west the zone in contact with the southern Archean furnishes frequent outcrops from the south quarter post of sec. 34, T. 42 N., R. 30 W., to the south quarter post of sec. 36, T. 42 N., R. 30 W., a distance of 2 miles. Then follows a gap of a mile in which no outcrops have been found. Near the north and south quarter line of sec. 31, T. 42 N., R. 29 W., they begin once more, and are supplemented by test pits as far as the west sixteenth line of section 32, next east.

Then follows another gap without exposures, $2\frac{1}{4}$ miles in length.

Near the north-and-south quarter line of sec. 34, T. 42 N., R. 29 W., outcrops begin again and continue for a mile to the east, with frequent interruption, as far as the north-and-south quarter line of section 35, where in the valley of the Sturgeon the southern zone broadens and joins the northern, in consequence of the general westward pitch which has carried the higher formations above the present surface of denudation. East of this point the quartzite is known in only a few scattered localities. In the southern part of sec. 36, T. 42 N., R. 29 W., it is in contact with the Archean on the south bank of the Sturgeon River. South of Felch Moun-

tain, in sec. 32, T. 42 N., R. 28 W., it outcrops immediately south of the abandoned Northwestern mine, and has also been found in drilling on the west and in test pits on the east of the natural exposures through a distance of half a mile. In sec. 33, T. 42 W., R. 28 W., a small ledge, a few feet square, occurs between the overlying dolomite and the Archean, 200 feet east of the road to the Calumet and Hecla (iron) mines. East of this the contact between the Archean and the Algonkian is a faulted one, and the quartzite is buried beneath the overlying formations.

The northern zone of the Sturgeon formation is not nearly so well exposed, nor for the most part does it fall within the artificial line that bounds our detailed work on the north. Secs. 34 and 35, T. 42 N., R. 30 W., on the west contain a few scattered outcrops, one of which is of exceptional petrographical interest and to be noticed later. The next exposures are 5 miles east, along and just north of the north line of sec. 35, T. 42 N., R. 29 W. The main northern zone of the Sturgeon formation coming from the west lies south of these exposures and is entirely covered. Between the two the tongue of Archean schists already described is faulted up. Two miles farther east quartzite again appears in test pits, low-lying outcrops and drill holes along the northern border of sec. 31, T. 42 N., R. 28 E., and in section 29, immediately north of section 32, is well exposed in a broad belt that reaches north almost to the east-and-west quarter line.

The quartzite often forms distinct linear ridges, which in spite of the chemical stability and apparent homogeneity of the rock seldom rise to the mean altitude of the neighboring Archean areas. An exception to this rule is the succession of ridges formed by the southern zone in the 3-mile stretch west of sec. 31, T. 42 N., R. 29 W.; these frequently overtop the adjacent Archean plateau. Very frequently, also, the quartzite zones occupy lower ground not only than the Archean but even than the immediately overlying dolomite. The southern zone, for some unknown reason, is a distinctly weak belt east of sec. 32, T. 42 N., R. 29 W., and for several miles forms the bed rock of the Sturgeon and the connecting valleys.

FOLDING AND THICKNESS.

It is extremely difficult in most cases to determine directly the attitude of the Sturgeon formation, owing to its generally massive and homogeneous character. This is due, as will be shown hereafter, to the completeness of

the recrystallization, in consequence of which the ordinary sedimentary features that it originally possessed have been almost entirely obliterated. Faint color banding, itself of secondary development, but no doubt preserving a distinction in original composition, alone remains, and only here and there, as a guide to the former stratification. By scattered indications of this sort, and by the better evidence afforded by the overlying dolomite, often very distinctly banded, it is known that the southern zone of quartzite on the whole dips toward the north. Southward dips also occur in this belt, by which it is known that subordinate folds occur within the quartzite itself. From the considerable variations in the surface width of the formation we are led to suspect the existence of more of these little folds than we are able to prove. However, the secondary syncline, which extends from the offset already referred to in sec. 35, T. 42 N., R. 30 W., for 6 miles to the east to sec. 35, T. 42 N., R. 29 W., and includes no formation higher than the quartzite, is very definitely determined.

In the northern belt of the Sturgeon formation the indications of dip are generally northward at very high angles. These indications, not in themselves conclusive, are reenforced by a corresponding attitude in the overlying dolomite, and it is therefore probable that there is a general, or at least widespread, overturn in the dip of the northern belt.

Since the contacts of the Sturgeon formation with the underlying Archean and with the overlying dolomite are (except in one case) covered, it is impossible to obtain the data for very accurate determination of its thickness. The uncertainty in most outcrops as to the dip of the quartzite introduces an additional difficulty. However, in sec. 35, T. 42 N., R. 30 W., on the west end of the range, and in sec. 33, T. 42 N., R. 28 W., 11 miles farther east, the covered intervals to the limiting formations are not great, and if the contacts are not faulted (which is far from certain), the minimum thickness is determinable within a reasonable limit of error.

In the western locality the surface width of the zone probably underlain by quartzite is about 500 feet. The quartzite itself is structureless, but the overlying dolomite dips northward at an average angle of about 70°. If the same dip holds in the quartzite, its true thickness is about 470 feet. In the eastern locality similar data lead to a thickness of nearly 430 feet. In these two sections the quartzite zone is much narrower than it is elsewhere, either because undetected faults have reduced it, or because it is

uncomplicated by subordinate folds. It is probably safe to conclude, in view of the uncertainties, that the average thickness of the formation is not less than 450 feet, and may be considerably more. In a preliminary paper on the district,[1] written before the field notes were fully analyzed, I have placed the thickness of the quartzite at about 700 feet; but this figure is probably too large.

PETROGRAPHICAL CHARACTERS.

The Sturgeon formation includes a few very closely related rock varieties, of which quartzite furnishes the great majority of the exposures. The quartzites are usually light gray in color, and break with a coarsely granular or glassy fracture. To the eye quartz is often the only recognizable constituent in the body of the rock, although the numerous joint and shearing planes shimmer with little silvery plates of muscovite. Occasionally a weathered surface is dotted with minute specks of an opaque pinkish substance, which leads one to suspect the presence of feldspar. Chlorite also is now and then visible in the darker varieties.

The quartzites are almost uniformly massive, except for the secondary fractures above mentioned. At scattered localities, however, a faint color-banding, due to the presence of layers of a pinkish hue, which are independent of the secondary fractures, seems to indicate the original stratification. The color bands are generally only vaguely defined; occasionally, however, they are numerous and sharp.

Closely associated with the massive quartzites are sheared quartzites, or micaceous quartz-schists. These rocks are merely varieties of the quartzite in which secondary shearing planes, with their attendant growths of new muscovite, are more abundant than usual. The shearing surfaces almost invariably intersect, with the result that the new structure tends toward the linear-parallel type, and is often as similar in appearance as it is in origin to the structure already described in connection with the sheared granites.

In a locality already referred to, on the south bank of the Sturgeon, in sec. 36, T. 42 N., R. 29 W., where the Sturgeon formation is in visible contact with the Archean, the quartzite is underlain by a considerable thickness of very fissile muscovite-biotite-gneiss, which incloses rather sparingly obscure pebbles of granite and quartz. This gneiss, which no

[1] Relations of the Lower Menominee and Lower Marquette series in Michigan (Preliminary): Am. Jour. Sci., Vol. XLVII, 1894, p. 217.

doubt was formerly an arkose rich in feldspar, has recrystallized and afterwards been sheared; the coarse micas to which the fissility is due, together with other new minerals, have grown between the fractured surfaces and recemented the broken mass. It affords beautiful examples of foliation parallel to a line.

The thin sections of the Sturgeon quartzite are of exceptional interest. The principal constituent is, of course, always quartz. With the quartz are associated, in much smaller amounts, and not necessarily all in the same section, numerous accessories, including muscovite, biotite, chlorite, microcline, orthoclase, plagioclase, titanite, rutile, zircon, apatite, and the ores. The relations of the quartz to the other constituents present very unusual features, and indicate that the metamorphic changes by which the present completely crystalline rock has been made from an original granitic sand have proceeded along lines not hitherto distinctly recognized in the formation of rocks of this character.

Among the large number of slides examined, a broad distinction can at once be made between those which show the effects of stress in a pronounced degree and those in which such effects are subordinate or hardly noticeable. Connecting these two classes is a perfectly graded series; and it is therefore certain that those of the first are merely the more or less modified varieties of an earlier stage, represented more nearly by the second. In the slides in which the effects of pressure are least apparent the microscopic characters are as follows: The background is composed of large irregular grains of quartz, the edges of which interlock with the most minute and sharp interpenetrations. The longest dimensions of these grains range from 1.5 to 6 mm., averaging perhaps 2.5 or 3. They often have a rather vague parallel elongation, which corresponds to the alignment of the minerals which they inclose. Scattered very abundantly through these large quartz grains are the accessory minerals, some predominating in one slide, others in another, but the micas and chlorite occurring in all. Through each slide the accessory minerals, with the exceptions noted below, lie with their long axes in a common direction, and frequently cross the serrated boundaries between adjacent quartzes. The inclusions in many cases have the form and other characters of clastic minerals, and thus preserve the only microscopic evidence of the original nature of the rock.

The included micaceous minerals are usually in small plates, ranging

from 0.05 to 0.75 mm. in longest dimensions, but few, however, exceeding 0.2. Many of these are bent and split, the clear unstrained quartz of the host penetrating from the frayed edges into the interior between the partly separated leaves. Biotite and muscovite, and sometimes chlorite, occur in the same individual, indicating alteration before inclusion in the quartz host took place. Besides its common occurrence as an alteration product of the biotite, a few rounded areas of chlorite, made up of little radiating tufts, seem to be pseudomorphs of garnet. Inclusions of titanite and magnetite, or a related ore, are not uncommon in the larger micas, and the biotite and chlorite sometimes inclose beautiful sagenite webs. Many of the smaller micas, however, have clear sharp edges and depart from the general parallelism of the other inclusions. These are either contemporaneous crystallizations or else, perhaps, were primary inclusions in former grains of clastic quartz which has since disappeared. Some of the clastic plates of biotite are bleached and include spheroidal blebs of red iron ore, similar to those described in the case of the Archean mica-schists.

The microcline inclusions are usually elongated in form, and frequently, particularly in the cases of the larger, have well-rounded clastic outlines. The long dimension, which usually coincides with one of the cleavages of the mineral, rarely exceeds 0.5 mm. or falls below 0.08 mm. The periphery is frequently partly surrounded by a thin film of biotite. Within the microclines are sometimes contained little blebs of quartz, which are not oriented optically with the host, and also, more rarely, small plates of biotite. The microcline individuals are sometimes broken into two or three differently oriented parts, which may be separated from each other, in which cases the quartz of the host has completely filled the interspaces. Fracture in the feldspar is often unattended with the slightest appearance of strain in the inclosing and cementing quartz, which extinguishes as one individual, and is therefore unmistakably to be attributed to stresses previous to the crystallization of the quartz.

Besides microcline, both orthoclase and plagioclase are sometimes inclosed in the large quartzes, but much more sparingly. They are invariably more or less decomposed, and are sometimes surrounded partially or wholly by a film of ferruginous material. They show the same phenomena of fracture, and occasionally of separation with penetration of the host, as the microcline, and occur in grains having a similar range in size.

Titanite is of frequent, zircon of rather rare, occurrence. The titanite is found not only inclosed, as already stated, in biotite and chlorite, but also in well-rounded clastic grains which are often bordered with an opaque ore. Zircon occurs in broken grains, without doubt clastic, and also in small crystals which show no signs of wear. These last were probably entirely embedded in original clastic grains of quartz.

Besides the above minerals of usual occurrence, small quartz grains of different orientation from the matrix are very rarely found included in the large quartzes of the general background. Only two or three such cases have been observed, and in these the included grain is surrounded almost wholly with thin plates of mica. It is believed that these are original clastic grains which, perhaps because protected by a film of material now represented by the micas, have escaped the general fate of their neighbors.

One or two composite inclusions, made up of microcline, the micas, and quartz, have also been noticed. These seem to represent original pebbles of granite or a crystalline schist.

The pressure effects begin with the appearance of optical strain and decided elongation in the large quartzes of the groundmass. This is followed by fracture, either along or quite independent of the original sutures, the crack often halting in the interior of a grain. The fractures preserve very roughly the same general direction, but frequently intersect at very acute angles, or come together in sweeping curves. The breaking is followed by movement, and this results in the production of a fine-grained quartz mosaic between the parted surfaces. In the final stages shown in the series of slides in my collection, the rock is made up of long, narrow lenses, each of which is an enormously strained quartz individual, separated by narrow anastomozing zones of very finely subdivided quartz. After the fracturing took place there seems to have been no further distortion of the lenses, for the edges of adjacent individuals follow similar curves, which are often reversed, and in many cases could be brought together with an accurate fit.

If the Sturgeon quartzite represents an original sandstone, it is evident from the facts stated above that the old quartz grains have undergone complete recrystallization. The usual conception, since the time of Sorby, of the process by which quartzites are formed from original deposits of sands is that new quartz is deposited around each original fragmental quartz grain,

in similar crystallographic orientation with it, and that neighboring grains thus enlarged finally interlock by mutual limitation of one another's growth. This explanation evidently can not account for the background of large interlocking quartz areas in these rocks, for if it were true it would be necessary to assume that the quartz grains were less numerous in the original deposit than those of almost any other mineral, in some slides even than the titanite or chlorite. There seems to be but one escape from the conclusion that the large quartz areas must each represent a number of original fragmental quartz grains, which, as deposited, must have lain in the rock with their crystallographic axes disposed entirely at haphazard; and that is the hypothesis that this quartzite was not originally a sandstone, but consisted mainly of soluble and easily replaceable material, such as limestone, with the fragmental particles scattered through it, and that the large quartzes of the background have replaced this soluble substance. I have been able to find no positive evidence to support this hypothesis, and I am compelled to believe that the rock was a sandstone in which, in some way not easy to understand, considerable numbers of adjacent quartz grains have united to form or have been absorbed into a new individual, leaving absolutely no trace of their former separate existence. The introduction of new silica, or the separation of silica from decomposing silicates in the rock itself, may well have been essential factors in the recrystallization. I shall make no attempt to explain the process further than to point out its probable analogy with the process by which the new microclines were formed in the Archean mica-schists.

The close alignment of the clastic minerals inclosed in the large quartz areas, their frequent fracture, and their occasional separation, indicate that the time of crystallization probably followed a period of stress; while the very vague parallel elongation of the individuals of the background in the unstrained sections would seem to show that they crystallized under static conditions. Unquestionable proof of a period of stress later than the crystallization is given by the numerous slides, in which these grains are seen to have suffered fracture and distortion. The microscopical study of the quartzites thus supplies important evidence, not afforded by the outcrops, as to the orogenic history of the district.

SECTION V. THE RANDVILLE DOLOMITE.

The Sturgeon quartzite is succeeded by a formation consisting, so far as is known, almost wholly of crystalline dolomitic rocks. Excellent exposures belonging to this formation are situated within a short distance of Randville station, on the Milwaukee and Northern Railway, and it may therefore conveniently be named the Randville dolomite.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Owing both to its great thickness and to its intermediate position in the series, the Randville dolomite in the Felch Mountain range covers a larger share of the surface than any other member of the Algonkian succession. The overlying formations are frequently interrupted, because of the changes in direction of pitch of the secondary synclines in which they occur. In these gaps the dolomite covers the whole interior of the synclinorium. Where the higher formations are present, they divide the dolomite into two or more parallel east and west belts, one of which lies south of the northern quartzite and the other north of the southern. Only in portions of secs. 35 and 36, T. 42 N., R. 29 W., where the rise in the axis of the main syncline has lifted it above the present surface of denudation, is the dolomite entirely absent from the main trough.

Natural exposures of the dolomite are not so numerous as of the quartzite, but they are more evenly distributed. Moreover, owing to its proximity to the Groveland iron formation, the dolomite has been penetrated by many test pits and diamond-drill borings put down in search of ore, and these supply important information in the covered areas. From the western end of the map to sec. 34, T. 42 N., R. 29 W., the dolomite is for most of the way separated into two or more parallel belts. The southern belt is especially well exposed in secs. 35 and 36, T. 42 N., R. 30 W., and in sec. 31, T. 42 N., R. 29 W., and for 2 miles to the northeast, beyond which it has been found only in test pits and drill holes. In the middle of sec. 35, T. 42 N., R. 29 W., the base of the formation is brought to the surface by the westerly pitch of the main fold and is well exposed along Sturgeon River.

North of the strike fault, which, as already described, has brought the

Archean mica-schists into contact with the dolomite and quartzite in the northern part of the same section, the Randville formation runs east in a single belt, which probably continuously widens as the throw of the fault diminishes. It has been found in several places in the north half of sec. 31, T. 42 N., R. 28 W., and near the east line of this section the appearance of the overlying mica-schists again divides it into two belts, which pass to the north and south of the Felch Mountain syncline. The northern belt has been proved by test pits only, but the southern is well exposed naturally in the neighborhood of the Northwestern mine. Other exposures also occur south of the unconformable mica-schists and quartzite of the upper series, in the central portion of sec. 33, T. 42 N., R. 29 W.

The dolomite is relatively a weak rock, and generally occupies lower ground than either the quartzite below or the iron formation above it. The belt in contact with the southern belt of quartzite especially is valley making throughout most of its extent. The outcrops usually form low, steep-sided knolls elongated with the strike and of slight relief above the basement; these occasionally unite into linear ridges, as in sec. 35, T. 42 N., R. 30 W. The northern belt is one of low general relief, from which, however, similar isolated knobs often protrude. The largest and most prominent of these is the peak in the northeast quarter of NW. $\frac{1}{4}$ sec. 36, T. 42 N., R. 30 W., which rises 80 feet above its base, covering 8 or 10 acres.

No actual contacts between the Sturgeon and Randville formations have been found, but from their close association and continuity, as well as from the structural characters, when these are determinable, they seem everywhere to be strictly conformable. Near the quartzite the dolomite becomes distinctly more impure and contains a larger proportion of silicates and quartz. It is altogether probable that between them come transition beds, as indeed is shown by some of the drill records. In one of these "talcky mica-schists, micaceous limestone, altered actinolite-schist, and quartzite" are described as being interbedded near the junction.

The determination of the thickness of the Randville formation is beset with the same difficulties as are encountered in the case of the quartzite, namely, the uncertainty as to the exact position of the contacts and the possibility of faults and subordinate folds within the formation itself. The best sections give a wide range of values from a minimum of about 500

feet near Felch Mountain to a maximum of nearly 1,000 feet in the western part of the district. While the discrepancies may be partly due to lack of precision in the data, it is probable that the thickness of the formation is not uniform, but really increases from east to west. On the Fence River, 18 miles northwest of Randville, the thickness is probably about 1,500 feet. Accordingly, accepting each of these determinations as approximately correct, 700 feet may be taken as a fair estimate of the average thickness of the Randville dolomite within the Felch Mountain range.

PETROGRAPHICAL CHARACTERS.

The outcrops of the Randville formation consist exclusively of dolomite, more or less pure, and always thoroughly crystalline. A few comparatively thin layers of schists, probably both micaceous and amphibolitic, and also of quartzite, are mentioned in certain drill records to which I have had access as occurring interbedded with the dolomite; and while the lithological determinations are perhaps not entitled to much weight, they at least prove the existence of rocks which are not dolomite within the formation. In the field, however, such interbedded layers do not outcrop, and they must constitute an extremely small part of the total thickness. From the results of my work the Randville formation appears as a lithological unit.

Macroscopically the dolomites are rather coarse-grained marbles, of various shades of color, of which pinkish or bluish white are the most common. They always inclose, more or less abundantly, large flakes and aggregates of tremolite, which are particularly noticeable from their projection above the weathered surface. Occasionally tremolite and other silicates are the most abundant, and sometimes, for small thicknesses, are essentially the only constituents. Quartz and chlorite are also often present, but in much smaller amounts. The weathered surface is usually dulled to a light brown or creamy yellow in a thin superficial skin, but is not deeply iron-stained, except when the silicates containing ferrous iron are present.

The following partial analyses of three specimens from different parts of the range show that the carbonate is normal dolomite. The insoluble portion consists chiefly of tremolite. These analyses were made for me by Mr. G. B. Richardson, a graduate student in geology in Harvard University.

Analyses of Randville dolomite.

	I.	II.	III.
Insoluble in HCl	2.0	9.7	29.1
Fe_2O_3	1.2	2.1	2.2
$CaCO_3$	53.2	48.9	39.3
$MgCO_3$	42.3	38.0	27.7
Total	98.7	98.7	98.3

The outcrops, while often entirely massive, usually possess decided structural features. These are indicated by color banding, by differences in texture, and by the banded arrangement of the components. Slight variations in the body color of the rock, proceeding from no distinguishable variation in composition, often occur in alternate parallel layers, which are persistent within the limits of observation. With the color banding often go variations in texture, which, however, are neither so regular nor nearly so persistent. The characteristic form taken by these is in thin layers, which as they continue open out into nodules. Such layers consist of closely packed crystalline grains, very much coarser than the body of the rock, which have grown normal to the boundaries. Adjacent layers are not strictly parallel and sometimes cross each other. They are believed to represent ancient fracture and slipping surfaces, which followed very closely the original bedding, in which the new carbonate individuals have had room for larger growth. The arrangement of the accessory minerals, especially the tremolite, also is usually a banded one. Layers rich in tremolite alternate with layers poor in tremolite, while within the layers the orientation of the tremolite individuals is usually at random. The structure brought out in these various ways is, on the whole, a parallel structure. It corresponds with the strike and dip in all the localities where these can be independently confirmed by the attitude of the adjacent formations, and it also has been thrown into minor folds. I therefore regard the structure as having originated partly in chemical differences in the material originally deposited and partly in secondary growths in the open spaces and rubbing zones determined by relative movements along the surfaces of easiest fracture at the time of the earliest folding, and for both reasons preserving in the subsequent metamorphism the true stratification of the formation.

Under the microscope the dolomites show no features of special interest. They are thoroughly crystalline rocks, chiefly composed of coarse grains of dolomite with which is associated a considerable number of accessory minerals. Of these the most important are tremolite, diopside, chlorite, muscovite, phlogopite, quartz, and rutile, while apatite, tourmaline, pyrite, and magnetite are rare.

The dolomite is by far the most abundant constituent in most of the slides, and furnishes the general background for the accessories. The shape of the grains in many sections is decidedly oval, and the long axes lie in the same direction, thus producing a foliation.

Tremolite is abundant in some of the sections, and is entirely absent from none. It occurs in long-bladed individuals and aggregates, usually bounded by the prism, but one or both pinacoids are also sometimes present. It includes portions of the carbonate background. Diopside is rather rare; it occurs usually in small single individuals, with sharp crystal outlines. It is sometimes surrounded by tremolite, from which it is distinguished by its high obliquity of extinction and its almost rectangular cleavage. Partings parallel to both pinacoids, as well as a transverse parting in prismatic sections, are also observable. Quartz occurs in irregular grains completely interlocking with the dolomite, and in some cases with tremolite. In the slides examined it is in all cases a secondary as well as a rare constituent. In no case is there any indication that it is clastic. Chlorite is an abundant constituent of some of the slides, while from others it is entirely absent. Muscovite in little frayed plates is plentiful in some sections. Quite possibly some of these may be original clastic particles. The most interesting mica, however, is phlogopite, which is very abundant in one locality near the base of the formation. It occurs in large, cleanly bounded plates, each of which is a multiple twin, and evidently a product of secondary crystallization. Some of these plates have been strongly bent, thus showing that the dolomite, like the quartzite, has been deformed since it crystallized.

The thin sections therefore show that the rocks of this formation have experienced even more nearly complete reconstruction than is shown in the case of the quartzites, for here none of the constituents, except possibly some of the smaller micas, are present in their original form. Also the evidence for disturbance after crystallization is of similar character and equally

strong. Accordingly, a close agreement in the sequence and in the character of the principal events thus indicated in the history of the two rocks may be recognized. These considerations make it quite certain that the recrystallization of the two formations was essentially contemporaneous. From the character of the accessory minerals in the dolomite it is probable that the crystallization was not accompanied by the introduction of foreign material from outside, in notable quantities, but consisted in a mineralogical rearrangement of the elements present in the rock from the beginning.

SECTION VI. THE MANSFIELD SCHISTS.

Above the Randville dolomite comes a formation composed chiefly of fine- to medium-grained mica-schists. Owing to their exceedingly soft character and small thickness, these rocks are exposed naturally in only a few localities in the Felch Mountain area. A series of phyllites less metamorphic but otherwise similar, and occupying the same stratigraphical position, immediately above the dolomite, outcrop characteristically at the Mansfield mine, and especially north of it, near the Michigamme River, in T. 43 N., R. 31 W. For these reasons it is convenient to name the formation for the Mansfield locality.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The existence of the Mansfield formation in the Felch Mountain area is known mainly from test pits and the records of diamond-drill borings and early explorations. Fortunately, these are so widely distributed that the persistence of the formation is well proved. Many drill holes have passed through it into the dolomite. Immediately above it comes the magnetic Groveland formation, which even when covered betrays its presence to the compass needle. With the upper and lower limits thus determined, and with the large body of data supplied by the test pits and records, there is no difficulty in indicating its approximate boundaries for the greater part of the map.

On the west, mica-schists belonging to the Mansfield formation have been proved by diamond drilling to occur between the dolomite and Groveland formations in the south half of sec. 34, T. 42 N., R. 30 W. Farther east there is a line of outcrops in the eastern portion of section 35, and the

schists have also been found in test pits on both sides of the western extension of the Groveland syncline in sec. 36, T. 42 N., R. 30 W. In sec. 31, T. 42 N., R. 29 W. (the Groveland section), they have been penetrated in 10 drill holes, besides numerous test pits, giving altogether a cross section more than half a mile in length from north to south. In the northern half of sections 32 and 33 numerous test pits have exposed the Mansfield formation, proving that it borders on both sides the narrow syncline, the interior of which for a mile and a half is occupied by the magnetic Groveland jasper. Through secs. 34, 35, and 36, T. 42 N., R. 29 W., and sec. 31, T. 42 N., R. 28 W., the mica-schists have not been discovered, probably both because they are but feebly represented and because but few test pits have been sunk through the Cambrian blanket. In secs. 32 and 33, T. 42 N., R. 28 W., the mica-schists have been found in scattered test pits and borings on both sides of the interior jasper of the Felch Mountain syncline, and also on the south side of section 33.

The thickness of the Mansfield formation is so small—not more than 200 feet—that it produces no very noticeable effects on the general topography, in spite of the ease with which it weathers. In the western portion of the district, through secs. 34 and 35, T. 42 N., R. 30 W., with the dolomite it underlies a broad low-lying plain, which is bounded on the south by a ridge of the Sturgeon quartzite backed by the Archean plateau. On the north, a broad ridge, through which diagonally pass the Archean granites and gneisses, the quartzite, and the dolomite, defines this valley as far east as the middle of section 35; in the northern and central portions of this section it spreads out into a swampy lowland, diversified by glacial sand plains, expressive of the gradual widening of the trough and of the generally horizontal attitude of the soft rocks of the interior. The most definite topographical feature directly due to the Mansfield schists is the narrow steep-sided valley which runs east from this lowland for nearly 2 miles, on the south side of the Groveland syncline. The ancient stream valley filled with the Cambrian sandstone, already mentioned, follows along this narrow belt.

PETROGRAPHICAL CHARACTERS.

The hand specimens from the various test pits, the drill cores, and the few small outcrops indicate that the Mansfield formation is quite uniform in character throughout the Felch Mountain area. The great majority of

the specimens are of fine-grained mica-schists, the color of which varies from light to dark, according as muscovite or biotite is the predominant mica. Garnets, in some localities, are very abundant, especially near the contacts with intrusives. It appears from the records of explorations that thin seams of jaspery iron ore interlaminated with the schists have been encountered in occasional drill holes and test pits, but no specimens of such occurrences have been obtained. Their existence is of interest, as showing the likeness in an important character of these more altered rocks with the slates occupying the same relative position in the Iron Mountain and Norway areas.

The outcrops and specimens are frequently well banded in lighter and darker layers, the color banding in some cases not coinciding with the schistosity. Just south of the Groveland mine, in a test pit which was sinking at the time of my visit, the color bands which mark the true stratification, as shown by the contact with the underlying dolomite, are closely crumpled and cut by the foliation of the rock, which is much the more distinct of the two structures.

Near the contact with the overlying Groveland formation the mica-schists become both more siliceous and more ferruginous, and there is accordingly a distinct passage between the two formations. This does not necessarily signify a transitional character in the original sediments, but may be altogether due to the downward transportation of silica and iron from the upper rock.

The mica-schists are generally very tender rocks, and the material on the dumps of test pits sunk in them is usually far gone in decomposition after a few years' exposure to the weather. From even the freshest specimens the little flakes of mica often rub off on the fingers. Where penetrated by intrusions, however, as in sec. 35, T. 42 N., R. 30 W., and in sec. 31, T. 42 N., R. 28 W., they become very much harder.

Under the microscope the rocks of this formation are seen to be in the main thoroughly crystalline, though very fine-grained, aggregates of biotite, muscovite, chlorite, quartz, and feldspar, with the iron ores, rutile, tourmaline, and apatite as the accessories. Garnets are abundant in some of the sections, and with these also occur actinolite, epidote, titanite, and an undetermined colorless amphibole in stout single prisms. In the eight thin sections which I have examined from this formation I have found no material

which is certainly original and fragmental, although almost every slide contains grains that may possibly be such. On the other hand, it is evident that the large majority of the individual grains have formed in place.

The micas are in most cases the most abundant constituent; sometimes muscovite, though usually biotite, predominates. The two micas are often intergrown. The biotite is usually very deeply colored, both brown and green, and, except in the thinnest slides, is almost opaque even in cleavage sections. The larger mica flakes do not exceed 0.5 mm. in length, and average not more than 0.25 mm.

Quartz generally occurs in irregular grains, full of fluid inclusions, and inclosing the various accessories. It frequently appears in little triangles in the interspaces between adjacent flakes of mica. Rarely part of the perimeter is rounded and embedded in a mica, thus suggesting a clastic origin.

Feldspar is very abundant in some of the slides and entirely absent from others. Both microcline and plagioclase occur, and in forms similar to the quartz. Biotite sometimes penetrates in irregular shredded edges and filaments into the interior of the feldspars, and in such cases may be a metasomatic product, as described by Irving and Van Hise[1] in the mica-schists of the Gogebic district. But much of the feldspar, as shown by its form and freshness, has recrystallized. The alignment of these minerals is with the schistosity of the rock, which they thus determine. When the schistosity cuts the lines of stratification, as it frequently does, the latter are but faintly marked in the thin section by very slight mineralogical differences. Thus a dark band, which may be very striking macroscopically, may be due merely to the predominance of deeply colored biotite; a light band, to the predominance of muscovite. Sometimes, however, in these bands a grain of quartz, or a stout flake of muscovite, lies out of the general orientation and with the direction of the band. Such grains are very possibly original. The schistose structure, as has already been stated, is determined by the general parallelism of the long axes of the constituent grains. Since the greater part, if not demonstrably all, of these grains have formed in this position, and have not been forced mechanically into it, the cases in which the schistosity cuts the bedding support the inference as to the time of the general recrystallization of the series grounded on the facts observed

[1] The Penokee-Gogebic iron-bearing district of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey, No. XIX, 1892.

in the lower formation, namely, that this time followed a period of great stresses. Also a period of still later stress has affected the recrystallized constituents of the schists, just as it has those of the quartzite and dolomite. It is shown by lines of fracture crossing the slides along which ferric oxide has infiltrated, and by occasional straining and bending of the quartz and mica.

Garnetiferous varieties of the schists are found in close proximity to basic igneous rocks, probably in every instance intrusives, and are evidently the result of contact metamorphism. With the garnets occur actinolite in felted mats and clusters, and abundant magnetite and pyrite. A colorless amphibole in large single crystals bounded by the prism and clinopinacoid, and giving low extinctions, is often associated with the actinolite.

SECTION VII. THE GROVELAND FORMATION.

The ferruginous rocks which compose this formation are well exposed in the central portion of sec. 31, T. 42 N., R. 29 W., in the vicinity of the Groveland mine, and thus may properly be termed the Groveland formation.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The magnetite, which is always an abundant constituent of these rocks, has made it possible to trace them for long distances throughout the trough, by means of the disturbances effected in the compass needles. The same disturbances had led to the sinking of a great number of test pits on the part of former explorers for iron ore, and the material thrown out of these has served to check and substantiate the inferences from the magnetic attractions. Finally, in several localities excellent natural exposures of the iron-bearing rocks occur. So, altogether, the available data as to the surface distribution of the Groveland formation are fairly satisfactory.

On the west the presence of the Groveland formation through secs. 34, 35, and 36, T. 42 N., R. 30 W., is shown by one principal and other minor lines of attraction, as well as by test pits and outcrops. The principal line of attraction begins in section 34, near the southwest corner, and runs to the northeast, in conformity with the strike of the northern belt of dolomite, finally ending in the northeastern portion of section 36. This line of attraction is very vigorous and strongly marked. Two other lines, parallel with the principal line, but more feeble and much shorter, cross the boundary between sections 35 and 36, and on the northern of these ferruginous rocks

outcrop in the western part of section 36. Near the center of section 36 another line, marking the western end of the Groveland syncline, begins and continues for a mile and a half east to the eastern portion of sec. 31, T. 42 N., R. 29 W. Along the western portion of this line are many test pits, and in section 31 the fine exposures of the Groveland hill.

Four hundred paces north of the center of sec. 32, T. 42 N., R. 29 W., another line of attraction begins, and may be followed toward the east without interruption nearly to the east line of section 33 of the same township. Along this line, which is comparatively feeble and crosses wet ground, there are but few test pits. In the eastern part of section 33, beyond the point at which the attractions cease, many pits have been sunk to and into the Mansfield formation, which is there somewhat ferruginous. From this point east for 4 miles the Groveland formation has not been recognized.

In the northern part of secs. 32 and 33, T. 42 N., R. 28 W., the ferruginous rocks are again well exposed on Felch Mountain for nearly a mile along the strike, and may be identified for half a mile farther by the vigorous disturbances produced in the magnetic needles. In the southeastern quarter of section 33 the Groveland formation is again encountered in a small and much-disturbed area, in faulted contact with the Archean.

The most conspicuous hills within the Algonkian belt owe their relief to the fact that they are underlain by the Groveland formation, but elsewhere this formation has left but little impress on the topography, perhaps because the local base-levels are cut nearly to the bottoms of the synclines in which it is preserved. The two hills referred to—Felch Mountain, in secs. 32 and 33, T. 42 N., R. 28 W., and the Groveland hill, in sec. 31, T. 42 N., R. 29 W.—stand 100 feet or more above the average level of the surrounding Algonkian territory, and in both instances the infolded secondary synclines are exceptionally deep and broad. The magnetic lines which indicate the other synclines pass through low ground, and the belts of disturbance are much narrower than in the cases of the two principal hills. There seems to be, so far as the collected material warrants a judgment, no lithological difference between the rocks of the narrow and those of the broad and deep synclines, and accordingly the relief of the latter is believed to be caused by their depth below the adjacent base-levels and not by their more resistant character.

PETROGRAPHICAL CHARACTERS.

The rocks of the Groveland formation have a general family likeness, which makes it very easy to distinguish them in the field from all the other members of the Algonkian series. Among them two main mineralogical kinds may be recognized, the usual one of which consists of quartz and the anhydrous oxides of iron, while the other, which is much rarer, is made up essentially of an iron amphibole, quite similar to the grünerite of the Marquette range, with quartz and the iron oxides as associates.

As seen in the field, the rocks of the first kind are generally siliceous, heavy, and dark colored, the weight and color, which has a tinge of blue, being due to the presence of abundant crystalline iron oxides. A large part of the silica is easily recognized as crystalline quartz, in some instances, indeed, in the form of detrital grains. The visible iron oxides occur both as little spangles of specular hematite and also in irregular dark-blue masses and single grains, the latter often having the crystalline form of magnetite. Many, if not most, of these last, however, seem to be really martite, as they give a dark purple streak, and in fine powder are not attracted by a hand magnet.

In the first kind there is much variety in external appearance, determined by the variable proportions in which the chief constituents occur and by the different ways in which these constituents are arranged. Considerable areas, for example, consist mainly of granular quartz merely darkened by the intimately mixed iron oxides, and in these, so far as the eye can judge, the rock is a ferruginous quartzite. Closely connected with such occurrences, or included most irregularly in them, are others in which the ferruginous constituents are so abundant and the quartz so subordinate that they would pass for lean iron ores. Between such rare extremes we find all intermediate proportions of mixtures of the quartz and the iron oxides.

One form of arrangement of the constituent minerals is in narrow parallel bands, in which the quartz and the iron oxides alternately predominate. Such alternations are sometimes so frequent and regular as perfectly to reproduce the lean "flag ores" of the Marquette range.[1] Regular banding, however, is not common. Usually the light or dark bands are

[1] Geol. Survey Michigan, Vol. I, Part I, by T. B. Brooks, pp. 93–94.

suddenly cut off, as if by faulting, or taper to thin edges, or occur in separated pebble-like forms. Neighboring lenses and fragments of bands are most frequently roughly parallel with one another, but often they are jumbled together in the greatest confusion. They no doubt represent an original more continuous banding, which has suffered brecciation. Masses thus shattered are also traversed and cemented by numerous small veins filled chiefly with quartz, chalcedony, and specular hematite. The positions in which the separated patches of the Groveland formation now survive, namely, in and near the bottoms of synclines, and therefore at the points where sharp turning and crowding together have taken place, sufficiently explain the extensive brecciation observed in these brittle beds.

Very prevalent in all the varieties of the first kind of rock, in massive, banded, and brecciated alike, is the occurrence of some of the constituents in small roundish spots, which give to the whole formation a very detrital aspect. In the quartzitic phases, as well as in the most ferruginous bands, the eye recognizes, besides the little grains of clear quartz, which seem to be unquestionably detrital, numerous small dots of blue hematite and bright red dots of jasper. These are more abundant in some layers than in others, but seem never to be entirely absent, and are exceedingly characteristic of the formation wherever found.

In a few localities the iron constituent is almost entirely in the form of little micaceous scales of specular hematite, which have a parallel arrangement. Hematite-schists, however, are not very common. The best examples occur in the northern part of sec. 36, T. 42 N., R. 30 W., along the northern syncline.

The second kind of rocks of the formation, the grünerite-schists, have been found in small thickness and in one locality only, namely, in the southern parts of sec. 33, T. 42 N., R. 28 W., where they underlie, in a series of small anticlines and synclines, banded siliceous beds composed of quartz and magnetite or martite.

Under the microscope the essential constituents of the first or prevalent kind of rock of the Groveland formation are quartz, magnetite, martite, and hematite. With these, much smaller quantities of chlorite, epidote, and apatite are generally associated as accessories. Of rarer occurrence are calcite and probably siderite, sericite, tremolite, grünerite, pyrite, limonite, chalcedony, rutile, titanite, tourmaline, microcline, and plagioclase.

Quartz occurs in two ways—first as rounded detrital particles, and secondly as grains which have crystallized in place. The detrital grains, which are easily recognized by their form, size, and freedom from inclusions of the ores, consist of single individuals, often surrounded with rims of later growth. They are also usually larger than the neighboring indigenous grains. While detrital quartz is not abundant and, indeed, is often entirely absent from the thin sections, its occurrence is of interest as conclusively establishing the sedimentary origin of the iron-bearing formation.

The secondary quartz grains are the most abundant constituents of the thin sections, and form the general background for the other minerals. They always inclose separate crystals of the iron oxides, usually in great abundance, and often also chlorite and little prisms of apatite. These grains usually have the shape of irregular polygons bounded by straight lines, frequently with reentrant angles, and adjacent grains completely interlock. In size the secondary quartz grains range from about 0.03 to 0.4 mm. in diameter. Grains of approximately the same size occur together in bands or in the rounded areas to be mentioned later.

The iron ores include both magnetite, or martite, and crystalline hematite, the former being much the more abundant. The magnetite and martite can not be distinguished in thin section, as their color in reflected light and crystalline form are the same. They occur in irregular bands composed of aggregates of crystals, the edges of which interlock with the adjoining and inclosed areas of quartz, and show the triangular, rhombic, and square sections of magnetite individuals. Magnetite also occurs in isolated, irregular aggregates interlocking with the secondary quartz grains, and of similar dimensions to these, but is especially abundant as single minute crystals interposed in the grains of secondary quartz, ranging in size from such as are barely recognizable under a No. 9 objective to octahedra 0.03–0.05 mm. in diameter. A single quartz grain $\frac{1}{4}$ mm. in diameter may inclose a hundred or more such minute individuals. Hematite is much rarer than magnetite, and seems to be found only in the secondary quartz grains or in veins. In the former it occurs in separate crystalline plates, of deep red color in transmitted light, under the same conditions as to number and size as the magnetic crystals. Throughout some sections, and in certain bands and rounded areas in other sections, it is more abundant as inclosures than magnetite. Such rounded areas formed of several quartz individuals, each

of which thus holds a great number of hematite plates, appear macroscopically as the little jasper dots already described. Chlorite and apatite are also often embedded in the secondary quartz grains, the former in thin plates and the latter in small hexagonal prisms. Epidote is quite common in small irregular areas intercalated between the quartz grains or in the magnetite bands.

Many of the slides contain a small amount of rhombohedral carbonate, much if not all of which is calcite. It occurs chiefly in the quartz bands, in irregular grains which interlock with the secondary quartz grains, and, like them, inclose little crystals of magnetite and hematite. Specimens the slides from which contain carbonates effervesce freely in scattered spots with cold dilute acid. Most of the carbonates are clear white under the microscope, and are evidently calcite. Sometimes, however, the carbonate areas have a very light-brown tint, and are partially surrounded with a limonite border and penetrated by brownish filaments along the cleavages. In such cases it is difficult to decide whether they are calcite stained with limonite, or siderite partially oxidized to limonite. However, if part of these areas are siderite it is nevertheless certain that the small magnetite and hematite crystals which they inclose have not been derived from them. These little crystals are inclosed in the carbonates just as they are in the adjoining grains of secondary quartz, while the alteration of the siderite, if it is siderite, is to limonite. Carbonates also occur with tremolite, quartz, chalcedony, epidote, and hematite in the numerous thread-like veins which traverse some of the thin sections.

The feldspars have been found in only a few thin sections, as well-scattered but minute angular grains of microcline and plagioclase. Many slides, however, contain areas of matted sericite and quartz which probably represent original grains of feldspar.

Rutile and tourmaline are also occasionally inclosed with the iron ores in the grains of secondary quartz. Small roundish areas of titanite, probably detrital, occur very sparingly in a few of the thin sections.

The most interesting features of the thin sections are certain very distinct structural arrangements of the quartz and iron ores. In almost every slide, in ordinary polarized light (with the analyzer out), the minute interpositions of the iron ores are seen not to be equally distributed throughout the background, but to be concentrated in round or oval areas, never

exceeding a millimeter in diameter. These oval forms are confined to the more siliceous bands, and are much more distinct in some of the slides than in others. Often the outlines are reenforced by rims of closely set magnetite individuals, somewhat coarser than the dust-like crystals within. The long diameters of adjacent ovals are parallel to one another and to the band in which they lie, and are often closely packed like pebbles. Occasionally the little grains of iron ore within the ovals have a distinctly concentric arrangement.

Between crossed nicols these areas are seen to have had in some instances a distinct influence on the crystallization of the secondary quartz. When they are large and closely packed, each oval includes a large number of interlocking quartz grains, and occasionally in such cases there is some difference in size between the quartz grains inside and those outside the ovals. In the triangular and quadrangular areas lying between the larger ovals, and bounded by curving segments of their perimeters, the secondary quartzes are frequently larger than those within, and are placed normal to the boundaries, precisely as if they had grown outward from the ovals into free spaces. Often, however, a single individual of secondary quartz lies partly within and partly without the oval. On the other hand, when the ovals are small, one or more may be completely or partially inclosed within a single quartz individual. The interlocking quartz grains within the large ovals show no indications of having formed in open spaces, even when the included iron ores have a tendency, as occasionally happens, to a concentric arrangement. The faulting and brecciation so plainly seen in many of the thin sections have also displaced and separated the oval areas. It seems perfectly clear to me that these forms represent a structure originally possessed by the rock from which the various phases of the iron formation have been derived, and which has been preserved through the subsequent metamorphism.

From the facts described above, it is evident that the Groveland formation is made up of highly metamorphic rocks, which still, however, retain some original clastic material as well as certain original structural characters. With the exception of the rather rare clastic grains of quartz, titanite, feldspar, etc., the minerals which now chiefly compose these rocks—namely, quartz and the crystalline iron oxides—are not clastic, but have crystallized in place. It is a matter of great interest, therefore, to determine, if possible,

in what form these constituents were present in the original deposit. On this question the microscopic structure seems to me to have a distinct bearing.

Forms similar to the ovals in these rocks occur in the iron-bearing formations of other districts in the Lake Superior region. In the Gogebic district of Michigan and Wisconsin, R. D. Irving and C. R. Van Hise[1] have supposed that such forms have resulted from processes of solution and redeposition after the rock was formed, and are therefore concretionary. They regard that portion of the formation—which they have named ferruginous cherts—in which such forms occur, as an alteration product from an original deposit of cherty carbonate of iron. On the other hand, J. E. Spurr[2] has shown that similar forms are exceedingly abundant throughout the iron-bearing formation of the Mesabi range of Minnesota, and are there original. In the least-altered stages Mr. Spurr has found that these oval and roundish areas are filled with a green substance, which chemically is a hydrous silicate of iron, in composition very close to glauconite, with which it is also optically identical. The oval and rounded forms, moreover, are those characteristic of glauconite in green sands of all geological ages. Starting with this original substance, which is very unstable when exposed to oxidizing and carbonated waters, Mr. Spurr has traced an interesting series of changes, the final result of which along one line is the complete oxidation of the iron to hematite or magnetite and the separation of the silica as chalcedony and quartz. Throughout these changes the original form of the glauconite grains is preserved in the new minerals. Without going into the details of these changes, and without accepting Mr. Spurr's conclusions in their entirety as to the steps involved, he has clearly shown, as I have satisfied myself from the study of the large number of Mesabi slides in my own collection, that the green glauconitic substance is the source of the iron and silica of the ferruginous cherts of the Mesabi range, and that the peculiar spotted structure of these cherts is inherited from the original forms of the glauconite grains.

Between the ferruginous quartzites of the Groveland formation and the ferruginous cherts of the Mesabi range there is a very close resemblance, especially in structure. The essential difference is that the former contain

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[1] Loc. cit., pp. 254–257.

[2] The iron-bearing rocks of the Mesabi range in Minnesota, by J. E. Spurr: Bull. Geol. and Nat. Hist. Surv. of Minn., No. X, 1894, 259 pp., 12 pls.

little or no chalcedony, the silica being crystallized quartz, while the latter have a great deal of chalcedonic silica. Also the former contain small amounts of detrital material, which the latter generally lack, but the essential difference between them is one of degree of crystallization only.

If the silica of the Mesabi cherts had originally crystallized entirely as quartz, or if after passing through the stage of mixed chalcedony and quartz it had subsequently crystallized as quartz, there would be no essential difference between the iron formations of the two districts.

There are, then, at least two possible forms in which the iron and silica of the Groveland formation may have been deposited originally, as indicated by the conclusions of observers who have studied the similar iron-bearing formations in other districts of the Lake Superior region in which these formations are less altered than here. Either of these forms—namely, a cherty iron carbonate, as on the Gogebic range, or a glauconitic greensand, as on the Mesabi range—could give rise, under the action of vigorously oxidizing waters, to rocks of the mineralogical composition of those in question, and since no trace of either original form has been found in the Groveland formation the choice between them may perhaps be regarded as still open. My own opinion, based on the microscopic structure which, as I interpret it, shows that the Groveland formation was in the beginning largely made up of rounded particles having the same general form as the glauconite grains of the Mesabi range, is that the iron and silica were originally present largely in the form of glauconite.

SECTION VIII. THE MICA-SCHISTS AND QUARTZITES OF THE UPPER HURONIAN SERIES.

Through the eastern part of sec. 32, T. 42 N., R. 28 W., and entirely across section 33, runs a belt of mica-schists and thin-bedded ferruginous quartzites which seem to have unconformable relations with the formations just described. These rocks are seen on the west in a cut in the Northwestern Railway in the SE. ¼ of the NE. ¼ of sec. 32. At the western end of this cut the strike is northwest and the dip northeast at an angle of about 35°. At the eastern end there is a decided bending in the strike to a more nearly east-and-west direction, and the bedding surfaces carry striations which dip east at an angle of 10°, all indicating that these outcrops probably lie on the south limb of a gently eastward-pitching synclinal fold, and

near the axial plane. East from this point similar schists and quartzites form a ridge, low and flat-topped, which extends immediately south of the railway almost to the east line of section 33, and sinks gradually beneath the great swamp of the eastern portion of that section. The formation noticeably disturbs the compass needles, and this fact, together with the rusty appearance of the outcrops, has probably led to the sinking of the numerous test pits by which the continuity is chiefly established. But low-lying natural exposures are not lacking.

North of the center of the NE. $\frac{1}{4}$ of sec. 33 similar schists have been found in two test pits. Also, parallel with the outcropping southern belt and a quarter of a mile or more farther north, a faintly marked zone of magnetic disturbances runs east and west through the swampy ground south of Felch Mountain and probably connects the last-mentioned occurrences with the exposures of the railway cut. It therefore seems likely that the low ground through the middle of sections 32 and 33 is wholly occupied by an open syncline of these soft and easily disintegrating rocks.

Between the exposed southern limb of this syncline and the southern Archean the lower Algonkian formations are found in the southeastern portion of section 33. Actual contacts are not visible, but there are noteworthy discordances in strike and dip, and especially clear proof of great disturbances in the lower rocks in which the upper have not shared. In the SE. $\frac{1}{4}$ of the NE. $\frac{1}{4}$ of the SW. $\frac{1}{4}$ of sec. 33, about 200 feet thickness of the Randville dolomite, striking east and west and dipping north at about 70°, is exposed between the Sturgeon quartzite below and the mica-schists to the north. Between the dolomite and the schists is a covered interval of some 40 feet. The latter also strike about east and west, but dip north at 30° or less. Between a quarter and three-eighths of a mile east of this locality (the interval being without outcrops) the Mansfield and Groveland formations lie against the Archean gneisses with a faulted contact. They have been thrown into a series of southeastward-pitching minor folds, and have been intruded by a mass of diabase and also by a pegmatite dike. The true strike of these formations at this locality is toward the northeast, and the dip, as shown both by the direction of pitch and the order of superposition, is toward the southeast. Five hundred feet north of this disturbed area and directly across the strike of the lower formations therein, the

upper schists and quartzites continue their southeastward strike without deviation.

These general relations indicate that the ferruginous mica-schists and quartzites are part of an upper series which overlies unconformably the Groveland and all the lower formations. This series has not been found elsewhere in the Felch Mountain area.

PETROGRAPHICAL CHARACTERS.

The rocks of this formation, as seen in the outcrops, are principally soft and deeply iron-stained mica-schists in which occur frequent thin beds of ferruginous and micaceous quartzite.

Under the microscope the schists are composed mainly of biotite, quartz, muscovite, and magnetite. Chlorite, as an alteration product of the biotite, is frequently abundant, and garnets also occur in some sections. These schists are much coarser in grain than those of the Mansfield formation, and are wholly crystalline. No clastic material has been recognized in the thin sections.

The quartzites also are thoroughly recomposed rocks, without recognizable clastic particles. Quartz is the most abundant constituent, and with it muscovite, biotite, and magnetite are constantly associated. The micas and the magnetite are frequently inclosed in a background of large interlocking quartz grains, which is very similar to the background of the Sturgeon quartzite. Such inclosures lie in general alignment throughout the thin sections, but, unlike many of the inclusions of the Sturgeon quartzite, they seem not to be clastic particles but to have crystallized in place. In one slide among the inclusions in the large quartzes of the background is a colorless isotropic substance, of low refraction, occurring in large polygonal areas, but without definite crystal form. It is usually stained with limonite, which has penetrated from the margins along straight lines, as if following cleavages. This interesting mineral, which is certainly not garnet, and probably not opal, deserves further investigation

The rocks of the upper series, like those of the lower series, are greatly altered. From their mineralogical composition and structure it is evident that as originally deposited they consisted of beds of mud separated by thinner beds of sand. But as they now stand they have been as greatly changed from their original condition as the bedded rocks below. Also,

since the time of metamorphism they have been subjected to stress, as is clearly shown by the optically strained condition of the secondary quartz grains and the bending and twisting of the micas.

From these facts we may reasonably infer that the general metamorphism of both series was accomplished after the deposition of the upper series and before the latter was folded. Reconstruction so complete as that shown by the upper series is not believed to take place except at considerable depths below the surface, and hence the part of the upper series now visible must then have been deeply covered by overlying rocks, which were afterwards entirely swept away before the deposition of the Cambrian. In the earth movements which folded this mass of material and brought it up within the reach of denuding agents, we may recognize the causes which have strained and broken the secondary minerals of both series alike.

SECTION IX. THE INTRUSIVES.

The Algonkian formations of the Felch Mountain area have been cut by later intrusives, among which both acid and basic rocks are represented. The latter have also been recognized in the Archean, in which, indeed, the freshest and least-altered occurrences have been found.

The acid rocks consist of fine- to medium-grained pink granites, occurring in narrow dikes. A number of these dikes have been found in the Sturgeon formation, both in the area of fine exposure on the south side of sec. 35, T. 42 N., R. 30 W., and also in secs. 34 and 35, T. 42 N., R. 29 W.

Two granite dikes are also known in the highest member of the lower series, but none have been detected in the Randville or Mansfield formations. One of these occurs on Felch Mountain, the other, a very coarse pegmatite, is found cutting the Groveland formation in the southern part of sec. 33, T. 42 N., R. 28 W.

Basic dikes and intrusive sheets are found in many localities. Some are highly schistose and greatly altered, others are massive and but little changed. They probably belong to many eras of eruption. The least altered are diabases, in one occurrence of which, from the Archean, the augites are almost intact.

CHAPTER IV.

THE MICHIGAMME MOUNTAIN AND FENCE RIVER AREAS.

By reference to the general map, Pl. III, it will be seen that an oval-shaped Archean area, about 11 miles long from northwest to southeast and having an extreme breadth of nearly 4 miles, runs through portions of Ts 44, 45, and 46 N., Rs. 31 and 32 W. The country to be described in the present chapter includes that portion of this Archean mass (together with the younger rocks on its eastern border) which lies east of the line between Ranges 31 and 32 W., as well as the territory to the south in the prolongation of the axial line, as far as the south line of T. 43 N., R. 31 W. A gap about 6 miles broad not covered by our work intervenes between this arbitrary southern boundary and the western termination of the Felch Mountain work at Randville.

In the northern portion of the area now under consideration (which lies along and is twice crossed by the Fence River) the geological structure is exceedingly simple, while in the southern portion, especially in the neighborhood of Michigamme Mountain, it is rather complex. The boundary between these two divisions falls in the neighborhood of the mouth of the Fence River in sec. 22, T. 44 N., R. 31 W. It is therefore convenient in what follows to refer to the northern portion as the Fence River area, and to the southern as the Michigamme Mountain area.

By referring to Pl. III, the broad geological structure of the whole territory of which the above-mentioned Archean oval is the center is evident at a glance. It is an anticlinal dome, the core of which is Archean, around which the younger Algonkian formations run in a series of concentric rings, on all sides dipping outward from the inner nucleus. In the Fence River area, on the eastern long side of the dome, the Algonkian formations have a constant eastward dip, and are free from important secondary folds. In the Michigamme Mountain area, however, which lies in the prolongation of the main axis of the dome, these encircling forma-

tions fall away gently to the south in a series of waves, produced by several concentric minor folds transverse to the main axis. Of these minor folds but one is at all distinct to the east of the general anticlinal axis, while to the west of this axis at least three are well made out within the Michigamme Mountain area. The much greater breadth of the Algonkian formations on the west side of the dome than on the east is probably due to the persistence of these minor folds toward the northwest.

The general character and aspect of the formations of the two areas and their succession is in so many respects identical with the formations of the Felch Mountain range that no doubt can be entertained that they are really the same formations. Nevertheless certain differences mark these rocks with a distinct individuality. These differences will be considered in detail in the descriptions of the several formations. In general they may be summarized as involving a great reduction in thickness of the Sturgeon formation, with a corresponding increase in the Randville dolomite, the appearance of surface igneous rocks at the Mansfield horizon in the Fence River area, and a less uniform and complete metamorphism in the whole Algonkian series.

SECTION I. THE ARCHEAN.

The rocks of the Archean core are well exposed through the west-central sections of T. 44 N., R. 31 W., while farther north in T. 45 N., R. 31 W., outcrops are few and scattered. Much less attention was paid to this area than to the Felch Mountain Archean; our work, as a rule, stopped with the location of the boundary, and, therefore, the following brief statements as to its character embody observations along the southern and eastern margins only.

The prevalent rock in the Archean is granite, varying from medium to coarse grain, and often carrying very large porphyritic Carlsbad twins of flesh-colored microcline. Banded gneisses and mica-gneisses and mica-schists, such as are so abundant in the Felch Mountain Archean, are rare but not entirely absent. While in many localities the granites are much crushed and even sheeted along adjacent parallel fractures, their originally massive character is sufficiently evident. They have the composition and structure of typical igneous granites. The primary minerals are entirely without definite arrangement.

In the Archean areas granites of two ages have been found, the younger in the form of narrow dikes. Basic igneous rocks, also in dike form, are rather abundant. One of these under the microscope proves to be a but little altered diabase, in which the augite is almost intact. These acid and basic intrusions are probably connected with the surface flows of like character which are so abundant at the Mansfield horizon along the Fence River.

Of much interest is the occurrence of a small mass of quartz-porphyry in contact with the Archean, and below the lowest Algonkian sedimentary formation. The locality is in sec. 21, T. 44 N., R. 31 W., in the southeast quadrant of the Archean oval. The upper surface of contact of this sheet with the lowest sediments is covered, and hence it is not entirely certain whether it is intrusive or extrusive, and therefore whether it belongs to Archean or Algonkian time. The general relations, however, appear to indicate that it is a surface flow which suffered erosion before the deposition of the basal Algonkian member, and is therefore to be classed with the Archean. The exposure is 250 feet long by 100 broad. The rock consists of a very finely granular matrix of a warm gray color, through which are sprinkled quite uniformly little grains of blue quartz, and larger rounded grains of pink feldspar. Flakes of biotite are scattered through the groundmass and coat the cleavage surfaces, which are developed in two distinct systems, intersecting at an angle of about 10°. Immediately below the porphyry is coarse porphyritic granite, sheeted in waving surfaces parallel to the contact, which dips eastward about 40°. The lower portion of the porphyry contains a number of fragments of the underlying granite, one of which is over 4 feet in length.

Under the microscope the groundmass is a fine-grained crystalline aggregate of quartz, greenish biotite, and a little feldspar. The quartz phenocrysts are beautifully corroded, and have the characteristic bipyramidal form, while the feldspars are extensively altered to biotite, sericite, and quartz.

Biotite-gneisses related to this porphyry in external appearance occur among the Archean outcrops inclosed in the "B" line of magnetic attraction in sec. 7, T. 45 N., R. 30 W., and may be described here for comparison. They are dark-colored, fine-grained rocks, which weather to light pink. They are eminently schistose, and the cleavage surfaces are coated with

biotite plates of medium size. Minute grains of blue quartz are occasionally distinguishable by the eye.

Under the microscope these gneisses have a fine to medium grained groundmass composed of quartz, microcline, orthoclase, plagioclase, green biotite, and muscovite, and a little scattered epidote. Within it are large roundish areas of quartz and feldspar, sometimes single individuals, but more often consisting of several fragments. The gneissic foliation is pronounced and is caused by a general elongation of the constituent minerals in a common direction. The only essential differences between these gneisses and the porphyries described above are this strong foliation and the coarser groundmass.

SECTION II. THE STURGEON FORMATION.

The Sturgeon formation as a distinct member of the Algonkian series is hardly known in this area apart from the Randville formation. Nevertheless, purely clastic sediments unmixed with the carbonates of calcium and magnesium were deposited and are now visible along one section between the Archean granites below and the dolomites above, and for these it is convenient to retain the name, although their total thickness is so small and their continuity so uncertain that they can not be shown on the geological map. The general conditions of sedimentation here were such, perhaps in consequence of the low relief of the neighboring land, that limestones began to form a relatively short time after the submergence of the Archean surface, so that the two lower Algonkian formations probably by no means represent equal periods of time with the same formations in the Felch Mountain range. The time represented by both together is perhaps not greatly different in the two areas, but since in the entire absence of fossil evidence it is impossible to draw the line of equivalence, while at the same time the lithological break is a sharp one, it seems desirable to carry over the Felch Mountain names, extending the Randville dolomite downward to the lower limit of limestone deposition, and retaining the name Sturgeon formation for the basal sediments which are free from carbonates.

These basal sediments are found only in sec. 15, T. 44 N., R. 31 W., where they are exposed in low-lying outcrops in the banks and bed of the Fence River. Elsewhere throughout the 10 or 12 miles through which the Archean extends in this area no outcrops have been found in the flat and generally swampy belt which intervenes between it and the dolomite above.

The exposures referred to consist of soft, light-weathering slates and graywackes, with which are interbedded layers of coarser texture. They are very evenly banded in pale shades of yellow, red, and green, and the structure thus brought out dips eastward at an angle of 52°. Besides this a secondary cleavage is quite prominent, especially in the finer-grained beds, also dipping eastward, but at a considerably higher angle. At the eastern side the slates are overlain by the lowest marble beds, here extremely impure and highly charged with chlorite and quartz sand. The thickness of slates exposed is about 100 feet, and between the Archean and the most western outcrops there is room for about as much more. The total thickness, then, can not exceed 200 feet.

A thin section of a specimen from one of the coarser layers shows it to be a graywacke, the most prominent constituent of which is quartz in small roundish and oval grains. These are embedded in a groundmass composed of chlorite in minute irregular plates, ferric oxide, and kaolin. The quartz grains while having generally clastic shapes are bounded by minutely rough edges which interlock with the fibrous minerals of the groundmass. Evidently much new quartz has been deposited round the original grains.

SECTION III. THE RANDVILLE DOLOMITE.

DISTRIBUTION AND EXPOSURES.

In the Fence River area the dolomite, as already stated, lies on the east side of the Archean, and occupies a belt over half a mile in width, which extends from the mouth of the Fence River on the south for about 10 miles to the north and west, to our western boundary near the northwest corner of T. 45 N., R. 31 W. In this distance it is twice crossed by the river, and on these natural sections and in their neighborhood the only known outcrops of the dolomite have been found. The northern river section passes through secs. 22 and 28, T. 45 N., R. 31 W., and discloses an excellent series of closely connected exposures for a distance of about 2,900 feet, measured at right angles to the strike. The southern section is 5 miles farther south, and is much less continuous, laying bare the extreme upper and lower portions only of the formation. Elsewhere through the dolomite belt the rock surface is concealed by swamps or glacial drift, to which last it contributes but few scattered bowlders of noticeable size.

South of the Archean dome in the Michigamme Mountain area the dolomite tops the low arch in a broad crumpled sheet, in the minor synclines of which the higher formations are more and more implicated as we go south. This broad sheet, with its included tongues of phyllite, extends to the south line of T. 44 N., R. 31 W., beyond which it disappears beneath the higher formations, except in a single narrow belt which continues along the main axis for about a mile farther south. Exposures sufficient in number to indicate several minor folds are found along the Michigamme River and scattered through secs. 28, 32, and 33, T. 44 N., R. 31 W., and sec. 4, T. 43 N., R. 31 W.

FOLDING AND THICKNESS.

In attitude the Randville formation in the Fence River division of the district is an eastward-dipping monocline, the inclination of which is generally moderate. The rocks are usually heavily bedded and nearly always show distinct alternations in coarseness and color, so that structural observations are made with much more certainty than in the Felch Mountain range. The more conspicuous minerals secondarily developed here—coarse carbonates and tremolite—have formed chiefly in the old planes of bedding. Oblique structures are generally absent except in the close vicinity of the basic dikes which intersect the formation along the upper river section. The surfaces of contact with the dikes stand at high angles, and nearly parallel to these the neighboring dolomite has well-developed cleavages, along which new minerals have formed, intersecting the true bedding. It is evident that the stronger igneous rocks in these cases have furnished resistant surfaces against which the dolomite has been kneaded in the general tilting of the series.

The eastward-dipping monocline is a simple one, yet the observed angles of inclination are by no means uniform. Thus, along the upper river section the dip ranges from 25° to 60°, with 40° as the mean of about a dozen observations. The variable dips are so scattered through the cross section as to indicate no widespread roll in the formation as a whole, but rather a great number of minor undulations probably distributed throughout its thickness. Such undulations are visible in favorable localities, as, for example, on the north bank of the river in the NW. ¼ of NW. ¼, sec. 28, T. 45 N., R. 31 W., where fresh surfaces have been exposed in blasting

for the dam. The light-blue and pearly-white layers of the beautiful marble here seen are thrown into a series of unsymmetrical folds. The western sides of the little anticlinals are short and overturned, while the eastern sides are long and gently inclined. Evidently, if the same system of secondary folding holds throughout the entire thickness of the formation, surface observations would show everywhere eastward dips at variable angles, dependent upon the portion of the fold which happened to constitute the particular outcrop, and gentle dips would be more abundant than steep dips. This would completely explain the observed variations.

Similar variations and lack of regular sequence in the dips are found in the southern river section. Five good observations range between 20° and 58°, all eastward, but none of the exposures is sufficiently extensive to show minor folds. The mean of these observations is about 40°.

The surface width of the dolomite zone on each section is a little less than 3,000 feet, assuming that a fair proportion of the covered zones on each side is underlain by the same formation. If the average observed dip is taken to represent the average dip of the rock, the thickness in each case would be a little over 1,900 feet. This is probably too great, and is certainly too great if the same kind of internal crumpling visible in parts of the upper river section is characteristic of the formation throughout. The average dip evidently would more nearly be represented by the dips of the long eastern limbs of the little anticlines. Assuming that these are less than the mean, we find the average of the dips below 40° to be 30° for each section. This gives a thickness of about 1,500 feet, which still is perhaps beyond the truth, but is probably much nearer it than the first value.

It is interesting to compare this result with the thickness of 500–1,000 feet obtained on the two Felch Mountain sections. A part of the increase is probably due, as already explained, to the earlier beginning of limestone deposition in the Michigamme area. But an important part of it is probably not depositional at all, but is the result of plications. The whole series here is but gently tilted as compared with the walls of the Felch Mountain trough, and hence the strong horizontal pressures have acted in a direction but slightly inclined to the bedding. The result has been the secondary crumpling within the formation which must contribute in an important degree to its present apparent thickness.

In the scattered outcrops of the Michigamme Mountain area the

dolomite strikes and dips toward all points of the compass. This irregularity is caused by the gentle arching over the general northwest-southeast axis, combined with much sharper local folding about a series of axes which run more nearly east and west. The best-defined east-and-west folds occur west of the main axis in sec. 32, T. 44 N., R. 31 W., in which three synclines and three anticlines are found along a north-and-south section 4,000 feet long. The two southern synclines are sufficiently deep to include the overlying Mansfield phyllites. The secondary folds die out toward the main north-and-south axis and broaden toward the west. East of the main axis but one secondary fold has been recognized, namely, the syncline which forms Michigamme Mountain. This is the deepest of the secondary folds, and the only one containing the Groveland formation.

PETROGRAPHICAL CHARACTERS.

The Randville formation in this area is richer in lithological varieties than in the Felch Mountain range. As originally deposited, a much larger proportion of sand and mud was mingled with the carbonates, and the progress of subsequent metamorphism also has been less uniform. Depending upon the interaction of these two factors, we find, as the extremes of variation, on the one hand coarse saccharoidal marbles, sometimes very pure, but most often filled with secondary silicates, and on the other hand fine-grained little-altered limestones, which occasionally are so impure as to be rather calcareous or dolomitic sandstones and shales. The more impure varieties occur, as might be expected, near the contacts with the adjacent formations.

On the Fence River, in sec. 16, T. 44 N., R. 31 W., the base of the dolomite rests on the Sturgeon formation. The rock is filled with grains of quartz and feldspar and scales of chlorite, and is so soft that it may be crushed between the fingers. In sec. 32, T. 44 N., R. 31 W., the top of the formation is in contact with the Mansfield slates, and between them is a complete series of transition beds. Near the junction the limestone becomes dark colored and contains thin bands in which the clayey material greatly exceeds the carbonates. These are succeeded by alternating beds of slate and impure limestone in nearly equal volume, and it is only high up in the slate member that the calcareous bands completely disappear. Apart from these belts of extreme impurity at the base and top of the formation, the presence of scattered fragmental grains of quartz and feldspar is rather general throughout.

The prevalent colors are white, various shades of pink, both light and

deep blue, and pale green. Where weathered, the usual colors are light brown or buff. The lighter-colored rocks in general are characteristic of the Fence River area where metamorphism is more uniform and more intense, and the darker colors of the Michigamme Mountain area to which the less crystalline forms are wholly confined. Bands differently colored are nearly always present in the same outcrop.

In the Michigamme Mountain area the torsional strains attendant upon the formation of folds in two directions have developed two systems of fracture in the dolomite. In these secondary quartz has formed, occasionally in large amount. Of much interest is the occurrence in close connection with such vein quartz of occasional thin bands of pegmatite, doubtless arising from the action of deeply derived waters. In similar spaces coarse secondary carbonates, tremolite, and oxides of iron also have commonly formed. Over the small anticlinal axes and domes of this area the original bands of the rock have often been shattered, and are now recognizable only in displaced fragments cemented together by the new minerals. In the Fence River area the general secondary folding has been attended with differential movements along the bedding, which left narrow open spaces where the adjacent surfaces failed to fit in their final position of rest. These spaces are now indicated by coarsely crystalline carbonates and silicates arranged normal to the original walls. Where the space was a wide one the outer walls are usually lined with coarse calcite, while the interior is filled with quartz.

In the Michigamme Mountain area certain pink bands of the dolomite have a beautiful oölitic texture, which is most clearly brought out in weathering by the geometrical regularity of distribution of the harder shells or cores of the little rounded grains. The forms are not different from and are quite as distinct as those in the oölitic limestones of recent deposition.

The chemical composition of the dolomites is illustrated by the following partial analyses by Mr. R. J. Forsythe, of Harvard University:

Analyses of dolomites from Michigamme Mountain area.

	I.	II.	III.
Residue insol. in HCl	14.25	9.34	....
$Al_2(Fe_2)O_3$	11.15	12.57	5.38
$CaCO_3$	47.18	45.98	36.60
$MgCO_3$	18.48	19.22	16.38

The ratio of $CaCO_3$: $MgCO_3$ is too great for normal dolomite, but approximates that for $2CaCO_3+MgCO_3$.

Under the microscope the chief differences in the various thin sections are in the degree of metamorphism and in the quantity and character of the foreign fragments. The least altered varieties are those highest in the series from the Michigamme Mountain area. These consist of a background of extremely fine-grained calcite, with a few rounded fragmental quartz grains, and scattered particles of chalcedony. Mixtures of small quartz particles, chalcedony, and calcite slightly coarser than the background occur in short vein-like gashes. The prevalent deep color of these rocks is due to the even sprinkling through the background of a black opaque pigment, which may be carbonaceous. Altogether the microscopic characters are those of a little-altered, slightly cherty limestone.

The more crystalline varieties of the dolomite contain several secondary minerals, namely, tremolite, diopside, chlorite, muscovite, phlogopite, pyrite, and the oxides of iron. Of these, tremolite is very common and abundant, especially in the Fence River area, where the rarer pyroxene, diopside, also is found. Phlogopite comes in but two of the thin sections, while muscovite occurs in nearly all. The general habit of these silicates is precisely the same as in the dolomite of the Felch Mountain range. They are developed pari passu with the passage of the unaltered dolomite into marble.

The fragmental inclusions within the dolomite are of interest. These are little pebbles of quartz, feldspar, mica, titanite, magnetite, and augite; and are evidently derived mainly from preexisting granites or gneisses. Titanite and augite are very rare; the others are represented in almost every slide. The quartz grains are seldom more than a millimeter in diameter and commonly are much smaller. While the general shape is oval or rounded in most cases, the perimeters are usually extremely irregular and interlock with the carbonate grains of the background, which indicates that they have been enlarged since deposition by the formation of new silica. This is very evident in the few instances in which the original smooth outline, or part of it, is preserved by a film of different material inside the present perimeter. The feldspar pebbles include orthoclase, microcline, and plagioclase, microcline being the common species. They are usually much decomposed and iron stained. The feldspars are especially abundant in the slides from the Fence River area.

The clastic pebbles give us striking proof of the general and severe internal strains suffered by the dolomite, the effects of which have healed over without a scar in the carbonate matrix. The pebbles are always optically strained. Very often they are fractured and the parts separated, and sometimes they have been reduced to small fragments. In these cases the breaks have been completely healed by the flow or redeposition of the groundmass in the interstices. These effects are found in greater or less degree in every thin section.

The oölitic varieties are very interesting under the microscope. They consist of little oval or round areas, averaging 2 mm. in diameter, packed together as closely as possible. Each oval consists of a single or compound nucleus, surrounded by several thin and very even concentric layers. The nucleus in a few cases is a single roundish quartz individual, evidently a clastic grain. In most cases, however, it is composed of a great number of minute quartz grains, or of several coarse calcite grains, with films of iron oxide between. The arrangement of these separate quartz and calcite individuals is such as to indicate that they have filled interior cavities. The surrounding thin layers are calcite in all cases. Sometimes two adjoining nuclei, each within its own rim of several layers, are together included within a common series of shells. In one such case the outside rim traversed the edges of the rings surrounding one of the nuclei with a decided unconformity, as if the latter had been eroded before the deposition of the former. The oölitic structure, I believe, has not hitherto been noted in limestones of undoubted pre-Cambrian age.

SECTION IV. THE MANSFIELD FORMATION.

The typical locality of the Mansfield formation is the Michigamme River valley in the vicinity of the Mansfield mine, which lies a mile west of the border of my field of work, and is described by Mr. Clements. The same formation, however, is present in the Michigamme Mountain area, where its relations to the adjacent formations are clearly defined. In the Fence River area rocks of very different character and derivation occur at the Mansfield horizon. These occur in typical development to the west, on the Hemlock River, and are hence called the Hemlock formation.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The Mansfield rocks of the Michigamme Mountain area consist of phyllites or mica-slates of various colors. They are found in the series of east-west synclines, which have already been described in connection with the Randville formation. The best exposures occur in sec. 32, T. 44 N., R. 31 W., between the center and the west quarter post, and still farther north along the south bank of the Michigamme in the northwest quarter of the section. They are also found round the western edge of the Michigamme Mountain syncline in sec. 33, T. 44 N., R. 31 W., and in sec. 5, T. 43 N., R. 31 W., but here the exposures are mainly in test pits. Test pits have likewise penetrated them in sec. 10, T. 43 N., R. 31, where they succeed the dolomites as the surface rock over the general arch. Their extent in the covered portions of this area is probably considerable, but the structure is so complex and the outcrops so few as to forbid any but the most approximate outlining of their general boundaries.

The geological position of the Mansfield rocks is free from doubt. In the principal syncline of section 32 they are seen to overlie the dolomites and to pass downward into them by a relatively slow gradation, while on the borders of the Michigamme Mountain syncline they are proved to underlie the Groveland formation. The passage to the higher formation likewise is graded, though more rapidly, and is marked in certain bands by an increase in clastic quartz grains and by changes in the character of the matrix in which these are set.

The portions of the surface underlain by the Mansfield formation are without special features, and are indistinguishable topographically in the gently rolling plain, the greater portion of which is formed in the dolomites. In section 32 the outcrops are miniature ridges elongated with the strike, the height of which, however, is less than the contour interval of the map.

FOLDING AND THICKNESS.

The folding of the Mansfield rocks, so far as it can be determined in this area, has already been described in the account of the preceding formation, which they overlie. The rocks are known only in the secondary synclines which lie transverse to the general direction of the main axis south of the Michigamme River. In the southern of these synclines, in sec. 32, T. 44 N., R. 31 W., between the limestone rims on the

north and south, a superficial width of about 1,800 feet of phyllites is exposed. The most southern exposures dip northward at a low angle. On the northern rim the true bedding is nearly vertical. Elsewhere the vertical cleavage structure alone is distinguishable. The upper limit of the formation is not found in this syncline. Making the most liberal estimate for possible minor crumples, it is improbable that a less thickness than 300 to 400 feet occurs here. On the eastern side of the main axis the phyllites below the Groveland formation are very much thinner than this, the thickness at the Interrange exploration, for example, being only about 100 feet; but there, as well as along the whole western edge of the Michigamme Mountain syncline, the lower contact with the dolomite is probably faulted. It seems entirely safe, therefore, to place the average thickness of the Mansfield formation in the Michigamme Mountain area at not less than 400 feet.

PETROGRAPHICAL CHARACTERS.

The Mansfield formation consists almost entirely of very fine grained mica-slates or phyllites. The prevailing colors are dark green, black, and light olive-green. These are often mottled irregularly with red, due to the infiltration of iron oxides along the secondary cleavages. The cleavage surfaces have a dull luster, caused by the parallelism of the micaceous minerals, which are too minute, however, to be distinguished by the eye or lens.

The phyllites are often finely banded in different colors and shades. Near the base of the formation bands of limestone and near the top thin bands of graywacke are interbedded, as has already been stated. Quartz and calcite lenses are not unusual in the minutely puckered portions of the formation.

The secondary cleavage is the prominent structure, and, indeed, the only structure of the outcrops where the color and texture bandings do not appear. Its general direction is transverse to the main arch, or nearly east and west, and its dip is almost vertical. The north-south compression thus appears to have been the stronger, or to have been active somewhat later in point of time than the east-west compression.

Under the microscope the phyllites are seen to be composed principally of fine leaves of muscovite and chlorite, often also with a little biotite, and with a variable and usually small amount of quartz, feldspar, and sometimes

calcite. Magnetite, ilmenite, and limonite are usually rather abundant. Pyrite also occurs in a few grains in nearly every slide. The differences in color depend mainly upon the relative proportions of the chlorite and muscovite, the former being characteristic of the dark-colored, the latter of the light-colored, rocks. The very dark-green or black varieties contain also an opaque and probably organic pigment in very minute particles. The quartz and feldspar grains are usually very small and irregularly shaped. The larger, however, of which a few occur in the slides from the less compressed rocks, have well-rounded contours. In other cases extremely flattened and strung-out lenses composed of many small particles represent what were doubtless originally single clastic grains.

Two varieties of cleavage are well illustrated in the thin sections, namely, that caused by the parallelism of the component minerals, and "ausweichungs-clivage." The former is characteristic of the coarser-grained varieties, and the latter of the finer grained, where the direction of pressure has made a large angle with the bedding. In some cases the little leaves of muscovite outline parallel and equal folds, less than 0.2 mm. from crest to crest, each of which is ruptured, sometimes with slight displacements, sometimes with none, entirely across the slide. The structure is most distinct in the red phyllites, in which the fractures and the arrangement of the muscovite plates are clearly outlined by the ferruginous stain. Each kind of cleavage in a different way tells the story of extreme pressure.

SECTION V. THE HEMLOCK FORMATION.

The Mansfield formation of the Michigamme Mountain area changes along the strike into rocks of an entirely different character, which, as already said, have been named the Hemlock formation.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The Hemlock formation in the Fence River area consists of several varieties of schists which occupy a belt between 2,000 and 3,000 feet in width between the dolomite on the west and the Groveland formation on the east. The best exposures occur on the two river sections already referred to (p. 431), but outcrops are by no means lacking elsewhere. At the northwest corner of the area, in sec. 6, T. 45 N., R. 31 W., the schists are found striking N. 60°–70° W., and dipping northeast about 40°. East

of the center of sec. 16, T. 45 N., R. 31, a few exposures occur, the structure of which strikes a few degrees west of north and dips eastward at angles of 45° to 50°. In sections 21 and 28, a mile and a half south, numerous outcrops in similar attitudes are found along the northern river section. In secs. 3 and 4, T. 44 N., R. 31 W., a few scattered outcrops only have been found, but throughout section 10 they are very abundant. For the next 2 miles south through secs. 15 and 22, T. 44 N., R. 31 W., only a few small exposures have been discovered which have the same northerly strike and eastward dip. Thus for a distance of 11 miles along the strike exposures occur at comparatively short intervals, the longest gap being 3 miles.

In general this belt is one of slight elevation above both the dolomite country on the west and the iron formation country on the east. The areas of best exposure are characterized by very rough topographical details, which are entirely lost in the generalized curves of the map. Abrupt strike ridges, separated by narrow ravines, succeed one another at short intervals. In the covered areas the surface, while retaining its general elevation, has been leveled off by the deposition of till in the hollows, and has the smoothly undulating contours characteristic of till-covered areas.

FOLDING AND THICKNESS.

No secondary folds have been detected within the Fence River area of the Hemlock formation, and on account of the metamorphism and cleavage structural observations are not possible from which they might be inferred. The only clear evidence as to the attitude of the rocks was afforded by the contact at one locality between beds of amygdaloid and agglomerate. There the dip is eastward at an angle of 50°. The surface width of the formation varies between 2,000 and 3,000 feet. If 50° is taken as the dip, the thickness would be from 1,500 to 2,300 feet. If the average dip is assumed to be 40°, or the average of the observed dips of the underlying dolomite, the thickness would be from 1,300 to 1,900 feet. Or if 30° be taken, the average of the lower dips of the dolomite, the thickness would be 1,000 to 1,500 feet. We may say, therefore, that the thickness north of the southern river section is probably not less than 1,000 nor probably more than 2,300 feet. South of the southern river section the thickness diminishes rapidly.

PETROGRAPHICAL CHARACTERS.

The exposures through section 10 and the northern part of sec. 15, T. 44 N., R. 31 W.—the southern river section—give us a nearly complete sequence across the Hemlock formation, the principal gaps being on the extreme east and west, thus leaving the details of the relations with the dolomites below and the iron formation above undisclosed. In this section of 3,000 feet in length, the rocks are chiefly chloritic and epidotic schists, with which are associated schists bearing biotite, ilmenite, ottrelite, and amphibole, greenstone conglomerates or agglomerates, and amygdaloids. These rocks are characterized by a generally fine and even grain, by a lack of sedimentary characters, and by a double structure. In most of the varieties minerals, which have formed quite independently of and later than these structures, are macroscopically conspicuous. The prevailing color is green, passing to dark purple and black in the varieties in which biotite, hornblende, and magnetite abound.

The distinction made in the field between the several varieties of the schists is a rough one, indicating the predominating minerals rather than implying the absence of the others. In fact all the varieties are intimately related. The chlorite-schists are very fine-grained green rocks, usually from their color evidently very epidotic; they weather to greenish or pinkish white. The cleavage surfaces are often plentifully sprinkled with little flakes of biotite. Frequently also black needles of ilmenite, brilliant plates of ottrelite, and large clusters of actinolite run irregularly through them, quite independent of the cleavages. The biotite-schists are much darker, and lack the green coloring. Through them also the same metamorphic minerals are frequently interlaced. By an increase in these minerals the passage to the other varieties in limited exposures is a very easy one.

Greenstone-conglomerates and amygdaloidal rocks occur in a few exposures. In the former, light green or gray aphanitic inclusions, of angular shapes, ranging from an inch to 2 or 3 feet in long diameter, are inclosed in a matrix of chlorite-schist or biotite-schist. The chlorite-schists often hold round or lens-shaped eyes of epidote, and epidote and quartz. That these are filled cavities can in most cases be shown only by the microscope, yet some of the larger amygdules have a banded structure evident to the naked eye. These rocks are of structural interest since they are the

only members of the area which possess undoubted bedding. The plane of contact between an amygdaloid and a layer of greenstone-conglomerate in SE. ¼ sec. 10, T. 44 N., R. 31 W., dips eastward at an angle of 50°.

Two well-marked systems of cleavage traverse all the rocks of the southern river section. The angle between their strikes is always acute toward the north, varying from 5° to as high as 34° in different exposures, while the direction of the bisectrix is almost constant at N. 8°–10° W. The dip of both systems is toward the east at about the same angle, namely 50° to 60°. The two systems are usually both well developed, so that the outcrop edges break down by weathering along zigzag lines. The character of the cleavages varies from fine partings which divide the surface into rhombs, sometimes extremely regular in the more aphanitic rocks to a single perfect schistosity capable of minute subdivision, along which the component minerals are visibly aligned, in the more crystalline. Along the cleavages seams of quartz and calcite have frequently formed.

Along the upper river section the rocks of the area are distinctly more crystalline, and are chiefly biotite-schists and biotite-hornblende-schists, the latter often very coarse. They are sometimes banded, but very irregularly, the lenticular character of the banding suggesting the rhombic cleavages of the southern section. Some of the finer-grained biotite-schists contain round or elongated areas of quartz and epidote, which resemble amygdules. With these are associated considerable thicknesses of sericite-schists, full of little eyes of blue quartz; these are evidently metamorphic acid eruptives. The width of the northern section is about 2,000 feet.

Under the microscope the Hemlock schists of the Fence River area have a general porphyritic habit. Two main divisions only are clearly distinguished. One of these is the fine-grained mica (sericite) schists, which are characterized by the presence of muscovite as well as biotite in the microcrystalline groundmass, and true phenocrysts of feldspar and bipyramidal quartz, while the other embraces all the other varieties, which, diverse as they undoubtedly are, have yet certain important characters in common and are connected by gradations. The sericite-schists are obviously metamorphosed acid lavas, and need not be described in detail here.

The origin of the second division, however, is far more obscure. The least altered of these rocks possess an exceedingly fine grained microcrystalline groundmass, made up of very pale chlorite and a colorless aggregate

with feeble double refraction, which seems to be quartz. Between crossed nicols the groundmass is almost isotropic, and it is by no means improbable that certain reddish patches here and there may really be glass. Little crystals of magnetite are abundantly scattered through the groundmass, and are often arranged in parallel curving lines, very suggestive of the flowage lines brought out on the surface of weathered rhyolites by the ferruginous stains. In many sections the groundmass includes minute lath-shaped plagioclase feldspars, much altered and with indistinct boundaries, which are often arranged in parallel lines. The groundmass also is generally sprinkled with little irregular grains of epidote and calcite.

In this groundmass are included in variable combinations and proportions much larger crystals and grains of common hornblende, actinolite, biotite, ottrelite, calcite, ilmenite, epidote, and zoisite. Of these biotite, calcite, ilmenite, epidote, and zoisite are the most constant and abundant.

Biotite is present in all or nearly all of the thin sections. It is always brown, and is characteristically developed in stubby individuals, very thick for their basal dimensions. These individuals are large and lie scattered through the slides. They frequently inclose portions of the groundmass. The mica cleavage most frequently stands across the cleavage of the rock. In many of the darker-colored schists, however, biotite plates intermediate in size between the large porphyritic individuals and the small chlorite plates of groundmass are present in large numbers, constituting a sort of secondary groundmass. These are generally aligned with the cleavage of the rock and are sometimes gathered in bands, but in color and stubby habit are similar to the phenocrysts.

Ilmenite in brownish-black prismatic sections is a common constituent. It usually lies at random through the slide. It incloses the quartz and epidote grains of the groundmass. Epidote and zoisite are exceedingly abundant, often in well-formed crystals. Many of the epidote and zoisite individuals contain darker colored inner nuclei, the nature of which is uncertain. In some cases the nuclei are irregular in shape and have the characteristic pleochroism of epidote, but are more strongly colored than the surrounding zones. In other cases they have sharp crystal boundaries, isomorphous with epidote, are brown in color, and inclose grains of magnetite; these may be allanite. The nuclei are too small, however, for determination. Generally they do not extinguish exactly with

the surrounding zones. It is probable that many of these nuclei represent an early generation of epidote, like the small irregular grains of the groundmass, which were subsequently enlarged to porphyritic size. Inclosures of zoisite are not uncommon in the large epidote individuals. Large lenticular aggregates of epidote with calcite, chlorite, and biotite are found partially replacing feldspar individuals, which were no doubt original phenocrysts. Similar aggregates unmixed with the remains of feldspar are not infrequent, and may reasonably be attributed to the same source. Epidote with quartz is also the common filling of the amygdaloidal cavities.

Common hornblende, actinolite, and ottrelite are very common as porphyritic constituents of the schists. Hornblende occurs in very large well-formed single crystals and clusters placed at random through the groundmass. It is characteristically associated with ottrelite and biotite, and often has formed somewhat later than the latter. It is always crowded with inclusions, which in the laminated varieties carry the structure through without reference to the position of the host. Ottrelite is abundant in some of the sections, and is distinguished by its characteristic pleochroism. It occurs in large individuals and multiple twins, and like the large hornblendes and biotites is full of inclusions.

The general characteristics of these schists then are, first, a groundmass composed of chlorite, quartz, magnetite, epidote, and in some cases containing plagioclase microlites, and secondly the presence in this groundmass of much larger porphyritic individuals of several secondary minerals. The varieties are determined by the varying ratio of the porphyritic constituents to the groundmass, by the nature of the predominant secondary minerals, and also by the differences in grain of the groundmass. This, while generally extremely fine grained is much coarser, but without mineralogical change, on the northern river section where the schists are more distinctly crystalline. The cleavage of the schists is determined by the arrangement of the minute particles of the groundmass, and not by the parallelism of the large secondary minerals. These last, further, are never faulted or broken, and in general are unstrained optically. They must have formed then after the compression and tilting of the series.

The origin of these schists, I think, is not doubtful. As important points of evidence we have, first, the absence of rocks possessing any sedimentary characters throughout the whole section. Next we have the

undoubted presence of lavas in the series, shown by the sericite-schists, amygdaloids, and greenstone conglomerates or agglomerates. Furthermore, the minerals which compose the schists are those which would result from the alteration, in connection with dynamic metamorphism, of igneous rocks of basic or intermediate chemical composition. Finally, the grain and character of the groundmass, and in some slides the presence therein of plagioclase microlites disposed in flow lines, point directly to an igneous origin and to consolidation at the surface.

Mr. Clements has reached similar conclusions for the formation above the Randville dolomite[1] on the western side of the Archean dome. There metamorphism seems to have progressed less far than in the Fence River area, and among the more basic rocks he has recognized andesites and basalts.

I conceive, then, that the Hemlock rocks of the Fence River area are a series of old lava flows, varying in composition from acid to basic, which first underwent dynamic disturbance, which developed the secondary cleavages, and afterwards, in a state of rest, the porphyritic minerals were formed. It is an interesting fact, for which I can suggest no explanation, that metamorphism is further advanced in the northern part of the area than in the southern, and the schists more distinctly crystalline. This is also true of the underlying dolomite.

SECTION VI. THE GROVELAND FORMATION.[2]

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The Groveland formation in this area, as in the Felch Mountain range, consists mainly of siliceous iron-bearing rocks, which hold much fragmental material, together with certain subordinate schists. While it is of wide extent throughout the area, its known outcrops are limited to three localities, namely: The vicinity of Michigamme Mountain, in secs. 33, T. 44 N.,

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[1] Volcanics of the Michigamme district of Michigan, by J. Morgan Clements: Jour. Geol., Vol. III, 1895, No. 7, p. 801.

[2] This formation was originally named by me the Michigamme Jasper (Am. Jour. Sci., March, 1894). The name Michigamme was subsequently used for one of the Upper Marquette formations, in the Preliminary Report on the Marquette District, 15th Ann. Rept. U. S. Geol. Survey. I now abandon the old name, although it is entitled to stand by the rules of priority, in order to avoid the confusion which would necessarily arise from its retention.

R. 31 W., and 3, T. 43 N., R. 31 W.; the exposures and test pits at the Sholdeis exploration in sec. 21, T. 45 N., R. 31 W., and the test pits at the Doane exploration in sec. 16, T. 45 N., R. 31 W. The last two localities are 1 mile apart, and the more southern is 8 miles north of Michigamme Mountain.

In spite of the poverty of the formation in outcrops, its distribution throughout the area has been well determined through its magnetic properties (following the methods described in Chapter II). Adjacent to the Fence River area of the Hemlock formation it gives rise to a strong magnetic line which passes through the outcrops and test pits of the Sholdeis and Doane explorations. To the north this line was followed to the southern side of sec. 32, T. 46 N., R. 31 W., where it is said to connect with a magnetic line followed by Mr. Clements from the western to the northern side of the Archean dome. To the south it continues into the Michigamme Mountain area to within a mile of the outcrops of Michigamme Mountain. There the magnetic line gives way to a broad zone of disturbances, feeble and difficult to interpret, but consequent I believe mainly upon the flattening of the formation as it begins to pass over the general northwest-southeast anticlinal axis. This zone connects directly with the exposures of Michigamme Mountain which produce similar irregular disturbances of the needles and which visibly constitute a thin crumpled sheet, on the whole but gently inclined.

For the stretch of 13 miles just described the Groveland formation occupies a continuous belt on the east side of the main anticlinal axis. In the Fence River area it lies east of and upon the Hemlock formation, while in the Michigamme Mountain area it holds the same relations to the Mansfield formation.

The eastern belt was not traced farther than a mile southeast of Michigamme Mountain. In the central and southeastern portions of T. 43 N., R. 31 W., however, in the direct prolongation of the anticlinal axis, we found a broad belt of slight magnetic disturbance, along the western margin of which lie volcanic rocks, dipping west. In sec. 26, T. 43 N., R. 31 W., this magnetic belt splits into two branches, one of which runs directly east for a mile and then southeast indefinitely, while the other maintains a general southerly course to the south line of the township. In section 26 large

angular bowlders evidently derived from the Groveland formation are found in the zone of magnetic disturbance, but no outcrops have been discovered. There can be little doubt that these disturbances roughly outline the position of the Groveland formation in the axial region.

Except in Michigamme Mountain, the most elevated point of the district, the Groveland formation is not topographically prominent. In the Fence River area it produces a more subdued and somewhat lower-lying surface than the underlying formation, but the difference is slight and is of little moment in comparison with the confusing effects of glaciation.

FOLDING AND THICKNESS.

In the Fence River area there is no reason to suppose that the Groveland formation contains within itself minor folds of any importance. Our knowledge of its attitude is supplied almost wholly by the magnetic observations, and these indicate that it has a general eastward dip like the underlying members of the succession. Here and there it may be divided into two or more parts by sheets of intrusive material, and also may be slightly crumpled, but on the whole it must be regarded as a single persistent sheet, having a general eastward dip.

At Michigamme Mountain the Groveland formation caps the hill in a well-marked syncline, the axis of which runs northwest and southeast. The structure is distinctly shown by the attitude both of the ferruginous rocks and of the underlying phyllites. At the Interrange exploration half a mile south, a secondary embayment of the same syncline, but more open, is found. These are the only folds of the Michigamme Mountain area sufficiently deep to include the iron-bearing rocks. The thickness of the formation can only be guessed at, as no complete section is exposed, and the data for determining its upper limit are decidedly shadowy. The magnetic observations indicate a breadth of from 400 to 600 feet, and as in the Fence River area it is certainly much thinner than the two lower formations, its thickness may be approximately 500 feet.

PETROGRAPHICAL CHARACTERS.

In general aspect the iron-bearing formation in this area is strikingly like that of the Felch Mountain range, and all the varieties there found are represented here also. It is therefore unnecessary to repeat the detailed descriptions already given. By way of broad comparison, however, it may

be said that the formation contains less iron than in the Felch Mountain range, and consequently the lighter-colored varieties are more abundant, that it contains more detrital material, and that in the Michigamme Mountain area the texture is generally closer and less granular. Moreover, in passing north from the Michigamme Mountain area to the Fence River area we find at the Sholdeis and Doane explorations that the lower portion of the formation is composed of ferruginous quartzite, which is succeeded higher up by actinolite-schists and grünerite-schists similar in all respects to the characteristic rocks of the Negaunee iron formation in the western Marquette district. In this change in character as the Marquette district is approached is found the lithological support for the view, first suggested by the distribution of the lines of magnetic attraction, that the Groveland formation is the southern equivalent of both the Ajibik quartzite and the Negaunee formation of the Marquette district. The passage to a more crystalline condition in going from south to north is also in accord with the like changes already noted in the lower formations.

Under the microscope the close texture of the Groveland rocks of Michigamme Mountain is seen to be due to the minuteness of the quartz grains of the groundmass, and to the abundance therein of chalcedony. The coarse quartz grains are all detrital and are often beautifully enlarged. In many slides feldspar pebbles occur, and in many also sericite and chlorite are prominent in the groundmass. The iron oxides, including both magnetite and hematite, in single crystals and also in aggregates, are well distributed, as in the Felch Mountain sections. A similar grouping of these in round pebble-like areas as in the Felch Mountain range is also beautifully shown. In one slide the matrix is a rhombohedral carbonate, probably calcite, in which are embedded quartz grains and the iron ores in single crystals and irregular aggregates.

The most interesting features of the thin sections from Michigamme Mountain are the pressure effects. In many slides the detrital quartz grains are strained to an extraordinary degree. In one case the stage was rotated 45° before the black wave of extinction completely traversed a little pebble 0.3 mm. in diameter. Almost every section is crossed in several directions by fractures healed by the deposition of coarse quartz and the iron oxides.

In the Fence River area the lower portion of the formation consists of quartzite, more or less ferruginous and micaceous. It contains beautifully rounded and enlarged grains of quartz, and also less abundantly rolled grains of microcline. Muscovite, biotite, and epidote occur, with the general background of interlocking later quartz. The more ferruginous layers have a groundmass almost exclusively of hematite, in which the clastic particles are set. The hematite is in parallel micaceous scales, which completely cover the cleavage surfaces. Above these layers come crystalline actinolite-schists and grünerite-schists, the former with garnets and both carrying particles of the iron oxides. These rocks are not distinguishable in the field or in thin section from certain varieties of schists of common occurrence in the Negaunee formation of the Marquette district.


R 31 W
R 30 W
T 47 N
T 46 N
Michigamme River
Spruce River
Perch Lake
BOUNE
Ægr
Au
Aln
Ala
1700
1600
21
22
23
24
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29
28
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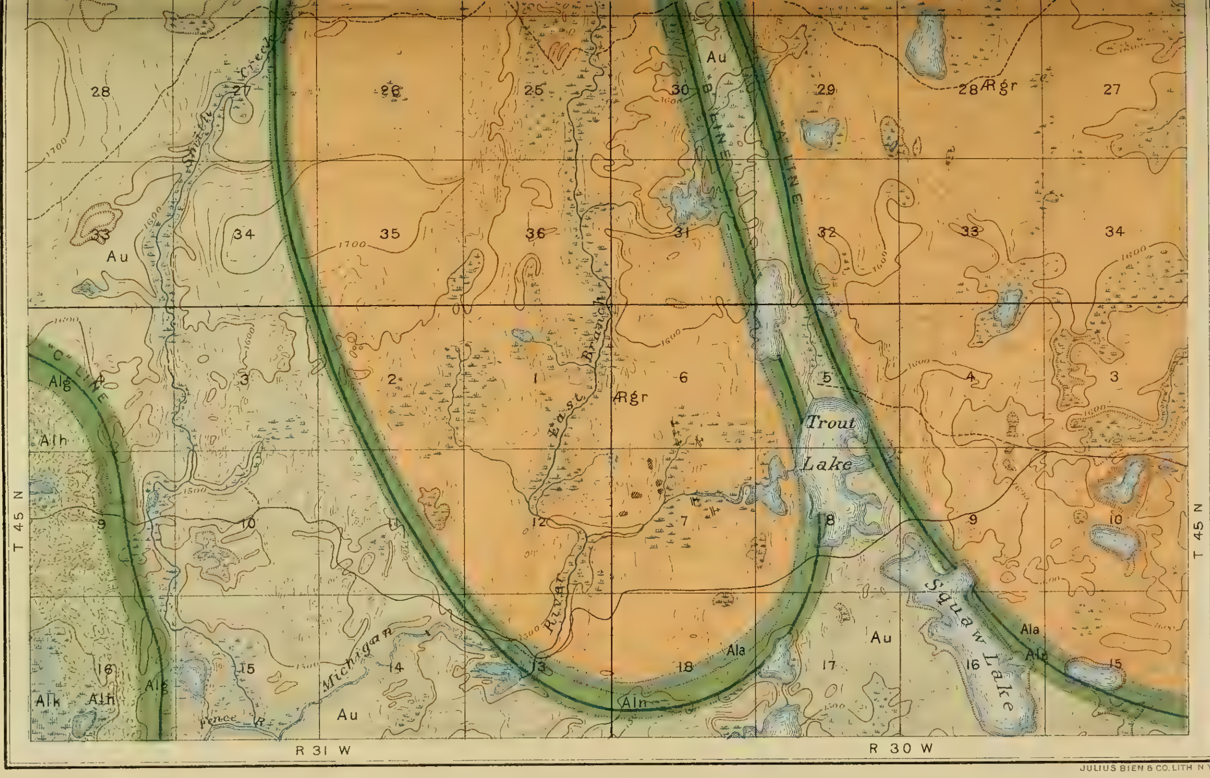

GEOLOGICAL MAP OF A PORTION OF THE CRYSTAL FALLS DISTRICT

WEST OF REPUBLIC

SCALE, 1 INCH = 1 MILE CONTOUR INTERVAL, 20 FEET

Outcrops without observed strike or dip — Outcrops with determined strike and dip — Outcrops with slatiness or schistosity

ARCHEAN	ALGONKIAN						
	LOWER HURONIAN				UPPER HURONIAN	INTRUSIVE	
GRANITE	KONA DOLOMITE	AJIBIK QUARTZITE	HEMLOCK FORMATION	GROVELAND AND NEGAUNEE FORMATION	UNDIVIDED	DIABASE	MAGNETIC LINES
Ærgr	Alk	Ala	Alh	Alg & Aln	Au		

GEOLOGICAL MAP OF A PORTION OF THE CRYSTAL FALLS DISTRICT

WEST OF REPUBLIC

SCALE 1 INCH = 1 MILE CONTOUR INTERVAL, 20 FEET

Outcrops without observed strike or dip · Outcrops with determined strike and dip · Outcrops with slatiness or schistosity

ARCHEAN · ALGONKIAN · LOWER HURONIAN

GRANITE · KONA DOLOMITE · AJIBIK QUARTZITE · HEMLOCK FORMATION · NEGAUNEE FORMATION

CHAPTER V.

THE NORTHEASTERN AREA AND THE RELATIONS BETWEEN THE LOWER MARQUETTE AND LOWER MENOMINEE SERIES.

From the northernmost outcrops of the Fence River area to the northern end of the Republic trough the air-line distance is about 11 miles. This intervening territory, on one side of which we find the typical formations of the Menominee district and on the other the typical formations of the Marquette district, remains to be described in this chapter. It may conveniently be referred to as the Northeastern area.

As was shown in the report on the Marquette district, in the productive portion of the Marquette range between Negaunee on the east and Republic on the west, the lower Marquette series consists of two or three clearly marked formations, which, perhaps, may further be subdivided according to individual taste.[1] The lowest of these, the Ajibik[2] quartzite, which rests on the Archean complex, is fragmental in origin, and is prevailingly a white vitreous quartzite, which in one or two localities is conglomeratic near the base. Often it is represented by a muscovite-schist as the result of the dynamic metamorphism of the original arkose. In the eastern part of the productive area of the Marquette district and along the northern side of the main fold, in the western part of the district, this formation is overlain by the Siamo slates.[3] Elsewhere the slates are not present, or are not known.

The next formation is the Negaunee iron formation,[4] which has already been referred to in Chapter II. This rock, which has many phases, as there noted, is clearly marked off from the lower quartzite by its great richness in iron and by the fact that over the whole Marquette district it nowhere appears to contain fragmental material, except in the transitional zone between it and the lower formations.

[1] The Marquette iron-bearing series of Michigan, by C. R. Van Hise and W. S. Bayley, with a chapter on the Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey, Vol. XXVIII, 1897, p. 221.
[2] Op. cit., pp. 528–529. [3] Op. cit., pp. 313–315. [4] Op. cit., pp. 328–407.

Above these conformable formations comes the unconformably placed Upper Marquette series, the base of which rests now on one member, now on the other, or on the Archean.

East and south of Negaunee, and extending thence to the shore of Lake Superior at Marquette, is a series of rocks which resemble lithologically neither the Upper nor the Lower Marquette series in the productive area. It consists, in ascending order, of quartzite with basal conglomerates, dolomite, and slates, and thus bears a close resemblance lithologically and stratigraphically to the three lower members of the Menominee series. This series, named by Wadsworth the Mesnard series, has been regarded by him as belonging with the Upper Marquette series, or at least as overlying the Lower Marquette formations just described. Maj. T. B. Brooks had earlier correlated the dolomite with the Lower Marquette quartzite, and had supposed that there was a gradual passage from one into the other along the strike. Mr. C. R. Van Hise has recently stated that its position is below the Ajibik quartzite.

This series is found only in the eastern part of the Marquette area, between Goose Lake and Lake Superior, a distance of about 6 miles. Elsewhere, over by far the greater part of the Marquette district, no member of it has been recognized.

The geological structure of the Marquette range presents the general features of an east-west striking complex syncline or synclinorium. The pre-Cambrian sedimentary rocks, with their associated intrusive and extrusive igneous rocks, occupy the trough, in which there is much local complexity of structure. The trough is flanked on the north and south by the older Archean crystallines.

At the western end of the district the peculiar Republic[1] trough branches from the main synclinorium, and runs southeast into the Archean rocks for 6 or 7 miles, having a nearly constant width of about one-half to three-quarters of a mile. In this trough the Algonkian rocks have been so closely compressed that they stand essentially on edge. The interior is occupied by the younger Upper Marquette quartzites and schists, between which and the underlying Archean walls the older Lower Marquette iron formation and quartzite here and there occur.

The northwestern end of the Republic trough is about the western

[1] Op. cit., p. 525.

limit of mining development, though not of exploration, on the south side of the Marquette synclinorium. Up to this point outcrops, producing mines, and old explorations are sufficiently abundant to permit the separate formations to be traced and mapped with comparative ease, and to indicate at least the larger structural features.

At this northwestern end of the Republic trough the Lower Marquette series makes an abrupt turn to the south, and may be followed for a mile or more by occasional outcrops and test pits. The Negaunee iron formation is persistently present beneath the Upper Marquette quartzite, and gives rise to a very strong and persistent line of magnetic attraction, which was followed in our work for about 12 miles to the south and southeast into the Northeastern area. For about 4 miles from the sharp turn at the mouth of the Republic trough it runs nearly due south; afterwards it turns somewhat to the east of south, and follows that course for about 6 miles, after which it turns more and more toward the east, and finally, where we left it, its course was only slightly south of east. That this magnetic line is caused by and marks the position of the Negaunee iron formation there can not be the slightest doubt, for that rock outcrops in a few scattered localities, occurs abundantly in the drift, and has been found in occasional test pits and drill holes throughout this distance. The underlying quartzite outcrops beneath the iron-bearing formation near the northern end of the line, but farther south it is entirely covered by the drift, so far as the territory has been examined. The overlying Upper Marquette rocks are also known to be present just west of the Negaunee formation as far south as sec. 19, T. 46 N., R. 30 W.

The magnetic line which accompanies the Negaunee formation may be called the A line. Taking into account the connected Republic trough and its exposures of the Lower Marquette rocks, it is seen that the A line partially surrounds a dome of the Archean crystallines, and that in going from the interior of this dome outward across the A line we pass from older to younger rocks. The dip along the A line is, therefore, on the whole, toward the west, although the observed dips at the few localities where determinations have been made are either vertical or slightly inclined from the vertical toward the east. The southern part of the A line, as far as it has been traced, passes through secs. 5, 8, 9, 15, and 16 of T. 45 N., R. 30 W. In section 5 it is just 5 miles east of the Groveland formation, which,

as was shown in earlier chapters, is a magnetic rock occupying a definite place in the Menominee succession, and is underlain by other typical Menominee formations, and finally by the Archean.

Between the A line and the magnetic line caused by the Groveland formation, which may be called the C line, is a third magnetic line, which may be called the B line. This was traced parallel to the A line and less than half a mile away, from near the south end of the latter to the north end, and finally entirely round an elliptical area, closing again upon itself at the starting point, the perimeter of the ellipse being 25 miles in length. Throughout this entire distance not a single outcrop could be discovered along the B line. Within the inclosed area, however, in secs. 6 and 7, T. 45 N., R. 30 W., and in sec. 19, T. 46 N., R. 30 W., several exposures of granites and crystalline schists were found, which left no doubt that the greater part of the area inclosed by the B line is occupied by Archean rocks of the same general character as those partially inclosed by the A line on the east and entirely by the C line on the west. The area between the A and B lines as far south as sec. 19, T. 46 N , R. 30 W., has been proved to contain the basal member of the Upper Marquette series. The southwestern quadrant of the B-line ellipse is nearly parallel to the C line and only 1½ miles away.

The known facts with reference to the B line, then, are these: (1) It represents a magnetic rock; (2) this magnetic rock completely encircles an Archean core. It may further be inferred with practical certainty that this formation, which carries such constant magnetic properties for 25 miles, must be sedimentary. With regard to its structure, the foregoing considerations would necessarily involve the conclusion that it dips away from the Archean core on all sides, and this conclusion is fortified by the unsymmetrical separation of the horizontal maxima on the magnetic cross sections. It follows, therefore, that on the eastern side of the oval, where the formation is parallel to the A line, it dips toward the east, and on the western side, where it is parallel to the C line, it dips toward the west. This conclusion is further supported by the dips within the ellipse in the outcropping Archean rocks that show structure. These all happen to lie east of the major axis, and all dip toward the east.

East of the B line, and between it and the A line, is found the basal member of the Upper Marquette series. The rock which is manifest in the

B line must, therefore, be older than any member of the Upper Marquette series. The Negaunee iron formation, represented in the A line, dips west, while the rock of the B line dips east. They are both older than the basal member of the Upper Marquette series, and are both younger than the Archean. They are both strongly and persistently magnetic. For 8 or 10 miles they run parallel to each other less than half a mile apart. Their broad structural relations to the Archean basement of the region are precisely similar. Therefore, although the rock that gives rise to the B line has never yet been seen, it may be concluded with the utmost confidence that it is the Negaunee iron formation, and that the A and B lines represent this rock brought up in the two limbs of a narrow and probably deep synclinal fold.

This conclusion carries the Negaunee iron formation 3½ miles farther to the west, and in the northeast part of T. 45 N., R. 31 W., leaves a gap of but 1½ miles between the Lower Marquette and the Menominee series.

Here, between the B and C lines, is precisely the same situation as between the A and B. One magnetic rock, represented by the B line, dips west; the other, the Groveland formation, represented by the C line, dips east. Between them no magnetic disturbances can be found. The area between them must have a synclinal structure, and if they are not one and the same formation each must undergo an extremely rapid and precisely similar change in lithological character (namely, the loss of magnetite) in a very short distance and be represented on the opposite side of the synclinal fold by a nonmagnetic formation. Each of these rocks is persistently magnetic in the direction of the strike for great distances. That each should independently lose its magnetite in the direction of the dip in this particular locality is very improbable. And, therefore, the grounds for the conclusion that the B and C lines represent one and the same formation are quite as firm as those upon which rests the conclusion that the A and B lines represent the same formation.

The greater portion of the Northeastern area is without outcrops, yet through the structural and lithological results of the magnetic work we are able to bridge over the gap and to show with a high degree of probability that the Negaunee iron formation of the Marquette range is identical with the Groveland iron formation of the Felch Mountain range. Further, when we recall the differentiation of the Groveland formation in the

northern part of the Fence River area into ferruginous quartzite at the base and grünerite-schist in the upper portion, it would seem probable that the Groveland formation represents the underlying Ajibik quartzite as well as the Negaunee formation of the western part of the Marquette range.

This conclusion has an important bearing on the interpretation of the early geological history of what is now the Upper Peninsula of Michigan. If the formations which constitute the whole of the Lower Marquette series over the 25 miles or more of the productive and best-known portion of the range are represented in the Menominee district and the intervening area by a single formation, and that the highest in the Felch Mountain succession—namely, the Groveland formation—the formations below the Groveland formation are all older than the Marquette rocks and do not occur at all within the productive portion of the Marquette range. Why are these lower formations absent?

To this question there seem to be two answers which are a priori possible. It is conceivable that the quartzite, dolomite, and slates of the south, or some of them, may have been deposited in a succession of unbroken sheets over the whole Marquette area, in continuity with the similar Mesnard formations on the east, and that afterwards the main Marquette area was elevated above the sea and entirely stripped of these formations by long-continued denudation. Finally, when the time of deposition of the Groveland formation came round, this elevated area had again been reduced to sea level, and subsided below it, so that the Ajibik quartzite and the Negaunee iron formation, and their southern equivalent, the Groveland formation, were deposited in an unbroken sheet over the whole. If this hypothesis is correct, two consequences should follow from it: First, we ought to find some discordance between the Groveland formation or the Lower Marquette quartzite and the lower formations in the marginal areas between the Menominee and Marquette, and the Mesnard and Marquette areas, respectively, or at least a gradual cutting out of these lower formations by the iron-bearing members and the lower quartzite, and, secondly, we ought to find, in the lack of discordance, rocks present in the areas of continuous deposition which represent the time of denudation.

With regard to the first of these consequences no verification is possible, at least in the territory between the Marquette and Fence River districts, from lack of outcrops. Throughout the Northeastern area, from the north-

western end of the Republic trough in T. 47 N., R. 30 W., to the C line in T. 45 N., R. 31 W., there are no exposures whatever of the Algonkian rocks which underlie the Groveland formation. Somewhere in this distance of about 11 miles the lower formations disappear, but whether by unconformity or overlap is an unanswerable question; nor (for the same reason) can it be definitely settled whether elsewhere farther to the south there is any discordance. That there is general parallelism between the Groveland formation and the lower rocks, and strict conformity in some places, is true. But this is not at all inconsistent with a period of erosion between them, if that erosion antedated the later and more severe orogenic disturbance.

In the Mesnard area the observed relations have been interpreted by Van Hise to mean that the lower formations disappear by overlap. The facts at present known on the Felch Mountain side are capable of the same interpretation, but they are not sufficiently definite to exclude the possibility of a period of erosion below the iron-bearing formation.

With regard to the second consequence—the deposition in the submerged areas of formations which would represent the erosion period in the elevated area—the evidence at hand is decidedly against the existence of such formations.

The alternative hypothesis is that the lower quartzite, dolomite, and slate formations of the Menominee area were not deposited over the western Marquette area at all, but disappear toward the north and east by overlap, and this hypothesis is much more likely to be the true one. We can suppose, as I have already pointed out,[1] that this part of the Upper Peninsula was a slowly subsiding area, the central portion of which, now occupied by the Marquette rocks, stood initially at a greater elevation above the encroaching sea than the rest. While the quartzite-dolomite-slate triad was going down in the Mesnard area on the east and the Menominee area on the south and west, the central Marquette area still remained above the sea. At last, when the Groveland formation began to be deposited, the Marquette high land was finally submerged and covered, as the sea marched over it, first, with a sheet of arkose made up of its own disintegrated débris, and, finally, with the same nonclastic sediments as chiefly compose the Groveland and Negaunee formations.

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[1] Relations of the Lower Menominee and Lower Marquette series in Michigan, by H. L. Smyth: Am. Jour. Sci., Vol. XLVII, 1894, p. 222.

CHAPTER VI.

THE STURGEON RIVER TONGUE.

By William Shirley Bayley.

DESCRIPTION AND BOUNDARY OF AREA.

The Sturgeon River area of Algonkian sediments, like the Felch Mountain area, is an east-west tongue of conglomerates, slates, and dolomites, very narrow at its eastern extremity and widening out toward the west until it finally plunges under drift deposits that separate it from the large Huronian area of the Crystal Falls district. The tongue occupies the western portion of T. 42 N., R. 27 W., the central and northern portions of T. 42 N., R. 28 W., T. 42 N., R. 29 W., and T. 42 N., R. 30 W., and the southern parts of T. 43 N., Rs. 28 W., 29 W., and 30 W. The best exposures of the rocks constituting the tongue are found in secs. 7, 8, 17, and 18, T. 42 N., R. 28 W., and in secs. 1 and 3, T. 42 N., R. 29 W., on or near the northwest branch of the east branch of the Sturgeon River; hence the name Sturgeon River tongue (Pl. LI).

On the south the sedimentary rocks are bounded by an area of granites, gneisses, hornblende-schists, and mica-schists, that are cut by granite and quartz veins, by dikes of diabases, and by other greenstones. This area separates the Sturgeon River tongue of sediments from the Felch Mountain tongue lying from 2 to 3 miles farther south. The exact line of demarcation between the granite-schist complex and the sedimentary rocks is difficult to draw, because for the eastern 7 miles the latter are bordered by greenstones whose position in the granite-schist complex or in the sedimentary series can not be determined at present. The line as drawn on the map places the greenstones in the Archean. It begins near the south side of sec. 7, T. 42 N., R. 27 W., and runs a little south of west to the quarter post between sections 17 and 18, in the next town west, then northwest to near

GEOLOGICAL MAP OF

SCALE 1 INCH = 1 MILE

Outcrops without observed strike or dip

Outcrops with slatiness or schistosity.

VERTICAL SCALE O

ARCHEAN

LOW

Granite

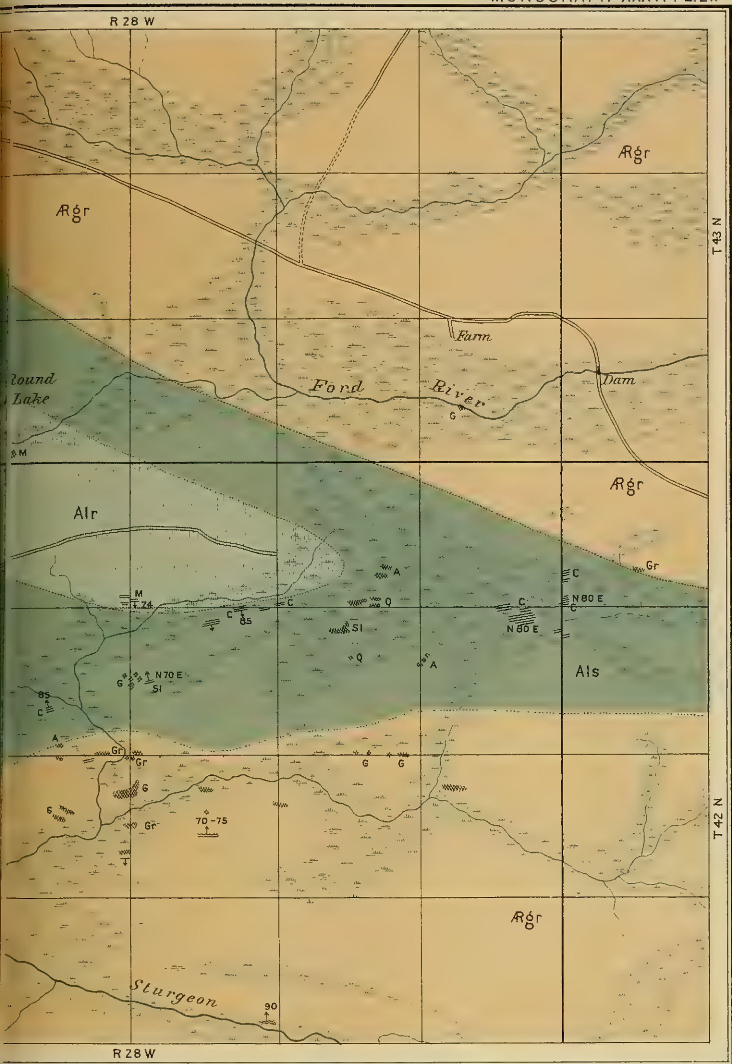
Ægr

Gr - Granite
G.S. Greenstone-schist

Sturgeon quart

Als

A-Arkose
C-Conglomerat
Sl-Slate
Q-Quartzite



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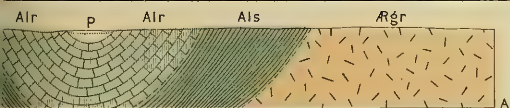

URGEON RIVER TONGUE

TOUR INTERVAL 20 FEET

Outcrops with determined strike and dip
Test pits bottomed in rock.

TION 1 INCH-1320 FEET.

KIAN — PLEISTOCENE

RONIAN

Randville dolomite

Alr — P

M - Limestone
Sl-Slate

GEOLOGICAL MAP OF STURGEON RIVER TONGUE

SCALE 1 INCH = 1 MILE CONTOUR INTERVAL 20 FEET

Outcrops without observed strike or dip

Outcrops with slatiness or schistosity

Outcrops with determined strike and dip

Test pits bottomed in rock.

VERTICAL SCALE OF SECTION 1 INCH = 1320 FEET.

ARCHEAN	ALGONKIAN		PLEISTOCENE
	LOWER HURONIAN		
Granite	Sturgeon quartzite	Randville dolomite	
Ægr	Als	Alr	P
Gr - Granite GS - Greenstone-schist	A - Arkose C - Conglomerate Sl - Slate Q - Quartzite	M - Limestone Sl - Slate	

the N. quarter post of sec. 13, T. 42 N., R. 29 W., and westward to near the southwest corner of sec. 12, T. 42 N., R. 30 W. From this point the line leaves the Sturgeon River tongue, curves southward, and returns east on the north side of the Felch Mountain tongue. The eastern boundary of the Sturgeon River Algonkian area is even less definitely determinable than its southern boundary, because of the thick drift covering the rocks. This boundary is placed at about the east lines of secs. 6 and 7, T. 42 N., R. 27 W., because just east of this line, in the NW. $\frac{1}{4}$ sec. 5, ledges of Paleozoic limestone occur. The northern boundary is the most indefinite of all. The southern portions of T. 43 N., Rs. 28, 29, and 30 W., are so deeply drift covered that but few ledges can be found in them, and these are widely separated. In sec. 6, T. 42 N., R. 27 W., and in secs. 13 and 24, T. 43 N., R. 29 W., are exposures of granite. These, so far as is known, mark the southern limit of an Archean area which stretches some miles northward and separates the Sturgeon River fragmentals from those of the Marquette district. The line marking the northern boundary of the Sturgeon River tongue begins at the southeast corner of sec. 6, T. 42 N., R. 27 W., and is assumed to run a few degrees north of west from this point until it reaches the west line of R. 29 W., where it turns north.

Between the northern and the southern boundaries of the sedimentary area as defined, and in the midst of the sediments, are two areas of granite, the rock of one of which is unquestionably, and that of the other presumably, older than the conglomerates within the tongue. The best defined of these two areas lies in the northern portions of secs. 7 and 8, T. 42 N., R. 28 W., and sec. 12, T. 42 N., R. 29 W. It measures about $2\frac{1}{2}$ miles in length and less than one-half mile in width. The extent of the second area can not be so accurately outlined. It occupies about three-fourths of a square mile and is entirely within sec. 3, T. 42 N., R. 29 W.

LITERATURE.

But few references to the existence of fragmental rocks in this portion of the Upper Peninsula of Michigan can be found in the literature of the region.

The early United States surveyors[1] reported the occurrence of talcose

[1] General observations upon the geology and topography of the district south of Lake Superior, by Bela Hubbard: Thirty-first Congress, first session, Executive Documents, 1849-50, Vol. III, No. 1, pp. 846, 847, 848, 855.

and argillaceous slates in Ts. 42 and 43, Rs. 29, 30, etc., of mica-slates in Ts. 41 and 42, Rs. 29, 30, etc., and of "calciferous sandrock" near the south boundary of T. 42 N., Rs. 27 and 28 W.

In a list of specimens gathered from these townships Burt[1] mentions sienitic greenstone, trap, granite, granulite, and talco-micaceous slate. On the land plats made by these surveyors conglomerate is noted on the west line of sec. 8, T. 42 N., R. 28 W., and marble at the south corner between sections 3 and 4 in the same township.

In 1851 Messrs. Foster and Whitney reported[2] the existence of an arm of Azoic rocks about 18 miles in length and 10 in breadth, extending easterly into Ts. 42 and 43 N., R. 28 W., and located its position on their map of the Upper Peninsula.

Brooks,[3] in his description of the northern iron belt of the Menominee district, refers to the existence of outcrops of hornblendic rocks, mica-schists, and gneisses, cut by trap dikes, which he regarded as equivalents of the various greenstone-schists exposed along the Menominee River. "Near the center of this hornblendic belt, in the north part of secs. 22, 23, and 24, T. 42 N., R. 29 W., a line of weak magnetic attraction was observed. This is regarded as an indication here of the existence of an iron-ore belt."

The gneiss, granite, etc., north of the north quarter post of sec. 31, T. 42 N., R. 29 W., he declares to have the appearance of typical Laurentian rocks. "If future investigations prove them to be Laurentian, a very troublesome structural problem would be presented here, as we would have Laurentian rocks conformably *overlying* beds unmistakably Huronian."[4]

The only distinct reference made by Brooks to the sedimentary beds of the district is in the following paragraph:[5]

A range of marble associated with quartzite, chloritic and talcose rock, and overlaid by a chloritic gneiss, with beds of chloritic schist and gneissoid conglomerate, the whole dipping at a high angle to the south, passes about 5 miles north of

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[1] Geological report of the survey of a district of township lines in the State of Michigan, in the year 1846, by Wm. A. Burt: Thirty-first Congress, first session, 1849–50, Senate Documents, Vol. III, No. 1, p. 84.

[2] Report on the geology and topography of the Lake Superior land district, by J. W. Foster and J. D. Whitney, Part II, The Iron Region: Thirty-second Congress, special session, 1851, Senate Documents Vol. III, No. 4, p. 14.

[3] Iron-Bearing Rocks (economic), by T. B. Brooks: Geol. Survey of Michigan, Vol. I, 1869–1873, N. Y., 1873, p. 161.

[4] Op. cit., p. 175.

[5] Op. cit., p. 176.

the North belt (i. e., the Felch Mountain tongue). These may represent the north side of the trough or basin, of which this iron belt is the south outcrop. No iron has, however, been found, so far as I know, on this range.

In Rominger's first report on the Menominee district only a single reference is made to this area. He declares that a series of test pits put down in the W. ½ sec. 26, T. 42 N., R. 29 W., and in the SW. ¼ sec. 14, T. 42 N., R. 30 W., are in decomposed granite.[1]

A specimen of the conglomerate referred to by Brooks as overlying the marble in the belt 5 miles north of Felch Mountain is described and pictured by Van Hise[2] in his paper on the Principles of North American pre-Cambrian Geology (see also Pl. LIII). It is stated to be from the Felch Mountain district. The more exact location of the ledge from which it was obtained is near the northwest corner of sec. 17, T. 42 N., R. 28 W., in the Sturgeon River tongue.

Thus the only distinct reference to a tongue of sediments north of the Felch Mountain range is that of Brooks, although the existence of sedimentary rocks in this portion of the Menominee district was reported by Hubbard and Burt. Brooks believed that the Sturgeon River rocks represented the northern rim of a syncline whose southern rim constitutes the Felch Mountain range, although both he and Rominger discovered a granite-schist complex underlying the country between the two areas of fragmental rocks.

RELATIONS BETWEEN THE SEDIMENTARY ROCKS AND THE GRANITE-SCHIST COMPLEX.

As has already been stated, the country between the Sturgeon River tongue of sediments and the Felch Mountain tongue is underlain by a complex of granites and various schists, traversed by fresh and altered diabases and by granite and quartz veins. Brooks recognized these rocks as presenting a Laurentian aspect, although he felt constrained to call them Huronian, because of the supposed structural difficulties involved in any other view of their age.

No contacts of this granite-schist complex with the bedded rocks of the Sturgeon River tongue have been discovered. Nevertheless, there can be little question as to the relative ages of the two series. As has been

[1] Geol. Survey of Michigan, by C. Rominger, Vol. IV, 1881, pp. 198–199.

[2] Sixteenth Ann. Rept. U. S. Geol. Survey, 1896, p. 801 and Pl. CXV.

stated, the granites and schists extend southward to the Felch Mountain fragmentals, and here they are unconformably beneath the latter. Moreover, since the Sturgeon River rocks and the lower members of the Felch Mountain series are identical in character, it is probable that they are of the same age, in which case the granites and schists that are older than the Felch Mountain rocks are older also than those of the Sturgeon River tongue.

The relations of the sedimentary series to the granites on the north have not been determined, because no contacts are exposed. The granites, however, can be traced northward until they are found unconformably beneath the rocks of the Lower Marquette series at Republic, and these, so far as is known, are the oldest sediments in Upper Michigan. There can be little doubt, therefore, that the relations of the sediments to the northern granites are the same as those with the southern schist complex.

The granites of the two areas surrounded by the sediments are probably of the same age as the northern and southern granites. The rocks of the area in secs. 7 and 8, T. 42 N., R. 28 W., and sec. 12, T. 42 N., R. 29 W., are demonstrably beneath the conglomerates, though their relations with the dolomites have not been determined. A well-marked contact between the granites and the conglomerates is exposed at the south base of a small hill of granite in the NE. $\frac{1}{4}$ sec. 7, T. 42 N., R. 28 W.[1] The conglomerate here is well bedded. Its strike is N. 60° W., and its dip almost vertical. It consists largely of pebbles and bowlders of granite identical with the granite composing the hill, and a matrix constituted entirely of granitic débris. The contact, though exposed for only a short distance, seems to be an erosive one. It is certainly not an igneous one.

From a consideration of the facts as given above, there can be little doubt that the rocks of the granitic areas within the Sturgeon River tongue and of those bounding it on the northern and the southern sides are older than the sediments within the tongue, though this has not been proved for the granites with respect to the limestones.

From the lithological similarity of the Sturgeon River fragmentals with those of the Felch Mountain district, and from the structural relations exisiting between the rocks of the two districts, it is practically certain that the Sturgeon River sediments are of the same age as the Felch Mountain

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[1] The exact location of the contact is 400 paces N., 280 W., of the southeast corner of section 7.

ones—i. e., Menominee (Huronian)—while the granites and schists belong to the Basement Complex on which the Lower Algonkian beds throughout Michigan have been laid down.

THE BASEMENT COMPLEX.

The Basement Complex rocks in the area studied comprise gneissoid granites, biotite-schists, and hornblende-schists, cut by dikes of greenstone and by veins of quartz and granite. The granites are best exposed in the NE. $\frac{1}{4}$ sec. 7 and the NW. $\frac{1}{4}$ sec. 8 and the NE. $\frac{1}{4}$ sec. 7, T. 42 N., R. 28 W., where they occur as bare knolls of a fairly coarse pink rock, separated from one another by stretches of sand. The best exhibition of rocks with the typical aspect of the Basement Complex is along the west half of the east-west quarter line of sec. 19, T. 42 N., R. 28 W., and south of the center of this section. Here we find hornblende-schists and hornblende-gneisses cut by veins and dikes of red granite and by greenstones that are usually schistose. Near the west quarter post of the section is a high hill bare of vegetation. On this hill the rocks are especially well exposed. In addition to the types already mentioned, there is present here a coarse white pegmatitic-looking granite that apparently cuts the hornblende-gneiss.

All the members of the Basement Complex in this area are so similar to the corresponding members of this complex elsewhere in the Lake Superior region that they demand but little description. They are described here only in sufficient detail to establish their character.

THE GNEISSOID GRANITES.

The gneissoid granites north of the fragmental tongue, and those of the two areas surrounded by the sedimentary rocks, are mediumly coarse aggregates of a dark-red feldspar, white quartz, and a dirty green chloritic substance. The red feldspar is in excess, sometimes to the exclusion of the other components, when the hand specimen resembles a dense red felsite. Almost all specimens are gneissoid. The constituents are usually lenticular, but in a few specimens, particularly those taken from near the contacts with the sedimentary rocks, they are drawn out into long slender string-like masses, giving the specimens a streaked appearance.

The microscopical features of all the granites are those common to these rocks elsewhere in the Basement Complex. They consist of clouded ortho-

clase, some plagioclase and a little microcline, quartz in varying quantity, and more or less green chlorite that seems to have been derived from biotite. All the constituents present abundant evidence of the effects of pressure. In the least-crushed rocks the quartz shows undulatory extinctions, and the feldspar grains granulation around their edges. As the crushing action increased, the granulation increased, so that the most crushed granites now consist of large grains of feldspar and of quartz in an aggregate of broken fragments of orthoclase, quartz, plagioclase and microcline, and a few wisps of green chlorite. Movement in the crushed rock mass has drawn out the granulated aggregate between the large grains of feldspar into bands and lines, thus producing the schistose structure noted in the hand specimens and in the ledges. In the more highly schistose granites a considerable quantity of new microcline and a small quantity of new plagioclase have developed within the granulated aggregate, and in a few instances muscovite has been found in fairly large plates of pale-yellow color. This muscovite occurs on the contact between the larger quartz and orthoclase grains, but more particularly in the granulated matrix.

The granites in the area between the Sturgeon River and the Felch Mountain tongues are not so abundant as those in the northern area of Basement Complex rocks, or in the areas surrounded by the sediments, but in their essential features they are identical with these. Occasionally the surface of a fresh fracture through these southern granites shows the outlines of porphyritic orthoclase crystals, but these crystals are not sufficiently numerous to impart a porphyritic aspect to the rock.

Some of the granite specimens examined from this district are so completely granulated that they can with difficulty be distinguished in the hand specimens from the schistose arkoses near the base of the fragmental series. In thin section they differ from the latter in containing no rounded quartz grains and in the possession of very little mica. The feldspathic constituents are nearly all decomposed, and very much of the quartz present in the granites is of secondary origin.

Thus in all essential respects the gneissoid granites of this district are like those in the Marquette district elsewhere described.[1]

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[1] The Marquette iron-bearing district of Michigan, by C. R. Van Hise and W. S. Bayley, with a chapter on the Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey, Vol. XXVIII, 1897, pp. 171–176.

THE AMPHIBOLE-SCHISTS.

In addition to gneissoid granites, the southern area of the Basement Complex contains a number of ledges of dark-colored schistose rocks. These, in some instances, are cut by dikes of granite similar to the granite already described.

These dark schists may be classed as greenstone-schists and as hornblende-schists. The former are heavy rocks, with dull greenish-gray luster and distinct schistose structure. They resemble closely in their microscopic as well as in their macroscopic features the schistose dike greenstones to be referred to later. They are doubtless altered or squeezed diabases or gabbros.

The hornblende-schists are usually fine-grained, bluish-black rocks, with a very even schistosity, closely resembling slaty cleavage. On the surfaces of cross fractures may be seen long slender prisms of glistening black hornblende arranged in as distinct lines as the lines of particles in an evenly bedded sedimentary rock. Often the cleavage surfaces are coated with thin layers of golden-yellow mica scales. In most specimens there may also be noticed a fine banding parallel to the foliation.

In thin section these hornblende-schists differ from the schistose dike diabases and from the greenstone-schists, referred to above, in the presence of large quantities of quartz, and of some biotite, and to some extent in structure. The greenstones owe their schistosity to the flattening of their components, while in the hornblende-schists this structure appears to be due largely to the crystallization of the hornblende in elongated prisms with their major axes parallel. The parallel arrangement of the amphibole in the latter rocks is thus much more pronounced than in the schistose greenstones.

The hornblende-schists are composed of hornblende, quartz, biotite, plagioclase, magnetite, and sphene.

The hornblende is in long prisms of the usual yellowish green color. The mineral is compact, but it is full of inclusions of quartz grains similar to those constituting a large part of the matrix lying between the amphiboles. It was evidently formed in situ as an original crystallization, and not, like much of the hornblende of the schistose greenstones, by the alteration of augite or of some other component of a basic crystalline rock. The biotite

is in small dark greenish-brown flakes interspersed between quartz and feldspar grains, which together constitute a matrix surrounding the other components. The quartz is unusually free from inclusions. It contains a few liquid inclosures and occasionally a few flakes of biotite and needles of hornblende. The plagioclase, where present, is in irregular grains with ragged outlines, as though a newly formed mineral. It appears to act the part of a cement surrounding the other minerals with which it is in contact. Small round grains of sphene and magnetite occur very abundantly scattered through the matrix. Often the magnetites are surrounded by borders of sphene; hence it is probable that this mineral is a titaniferous variety and that the round grains of sphene are pseudomorphs after magnetite grains that have been completely altered.

In a few specimens large colorless areas with the outlines of porphyritic crystals are observed in the midst of the finer-grained groundmass of schist. Between crossed nicols these break up into a coarse-grained aggregate composed of the same minerals that constitute the rest of the rock, except that in it altered plagioclase is common and amphibole is rare. These probably represent phenocrysts of plagioclase which have suffered alteration into quartz and new plagioclase that may differ somewhat from the feldspar of the original crystal.

The banding of some of the hornblende-schists has already been referred to. Under the microscope the only differences noted in the bands are the quantity of hornblende present in them and a variation in the coarseness of grain. The coarsest of the bands have the composition and structure of the schistose greenstones. They contain large quantities of plagioclase, both fresh and altered, and large grains of hornblende that are not in the definite prismatic form characteristic of this mineral in the main mass of the rocks.

ORIGIN OF THE AMPHIBOLE-SCHISTS.

From the gradations often observed between the hornblende-schists and the greenstone-schists, it is plain that the two rocks are genetically related. The latter, from their similarity to schistose dike greenstones in composition and structure, are believed to have been derived from massive diabases or gabbros. The hornblende-schists are in all probability derived from similar basic rocks, though the presence in them of what appears to

have once been plagioclase phenocrysts may indicate that the original rocks were in the form of lavas.

The principal difference between the hornblende-schists and the greenstone-schists seems to be in the nature of the amphibole in the two rocks and in the presence of quartz and newly formed plagioclase in the first named. The materials of the greenstone-schist were derived from the alteration of those of the original rock, as were also those of the hornblende-schist, but the former now consist mainly of the direct products of this alteration, whereas in the latter the substances now existing have been worked over and entirely recrystallized.

THE BIOTITE-SCHISTS.

Mica-schists are not common in the Sturgeon River tongue. They constitute by no means so large a part of the Basement Complex in this district as they do in the other portions of the Lake Superior region that have been studied. Indeed, only a few ledges of this rock have been observed in the country between the Sturgeon River and the Felch Mountain sedimentary tongues, and most of these are along the southern edge of a greenstone knob 300 to 400 paces north of the southeast corner of sec. 17, T. 42 N., R. 28 W.

The mass of this knob is a dark hornblende-schist. On the south side of the top of the knob this rock is in contact with a very evenly banded or streaked rock of a general dark-gray color. In the hand specimen it resembles very closely a fine-grained banded augen-gneiss. Near its contact with the hornblende-schist the rock is apparently porphyritic, with phenocrysts of feldspar from 1 to 15 mm. in length, and an occasional one of quartz scattered through a matrix composed of narrow alternating bands of almost black and light-gray material. On cross fractures of the rock the phenocrysts are seen to be drawn out in the direction of the bands. Cleavage takes place very readily along the planes of the banding, yielding surfaces covered with tiny scales of black biotite. A little farther from the contact the light-colored bands are thicker and more distinct. At first glance they appear to be uniformly thick for long distances, but a more careful inspection shows that they wedge out rapidly and are replaced by other bands of the same character. The dark bands are not thicker than

sheets of paper. They are the cross sections of the mica coatings on the cleavage planes.

The inspection of this rock in the hand specimen and in the ledge leads to the same conclusion—that it is an intermediate or an acid lava, a porphyrite, or a porphyry that was squeezed until it became schistose and sheared until it became fissile.

Under the microscope the feldspar phenocrysts, though much decomposed and filled with inclusions of quartz, muscovite, and other decomposition products, are well enough preserved to exhibit in some places twinning striations. The greater portion of the phenocrysts are untwinned. The twinned material borders the grains, fills in cracks between Carlsbad twins, and is irregularly distributed through the untwinned material, occurring more particularly in those places where the decomposition of the original feldspar is most complete. The twinned feldspar is fresher than the untwinned variety. This fact and the manner of its distribution indicate a secondary origin for it. The quartz phenocrysts are rare. They present their usual characteristics.

The groundmass in which the phenocrysts lie is a fine-grained aggregate of biotite, quartz, and plagioclase. The biotite is a greenish-brown variety. It occurs in large plates arranged in parallel position and in small flakes occupying the same parallel position and lying between the quartz and the plagioclase grains. The banding noticed in the hand specimen is due to the arrangement of the large biotite flakes in bands. These are separated from each other by bands of quartz and plagioclase that are free from the large biotites, though they contain innumerable small flakes of this mineral. Only when a porphyritic crystal lies in the way of the bands do these depart from their uniform directions. Here they bend around the phenocrysts, leaving on both sides of them little triangular areas in which the components are much finer grained than elsewhere in the rock.

The light-colored components are quartz and plagioclase. These minerals are in small grains that appear to be intercrystallized in the manner of the secondary aggregate that constitutes the fine-grained matrix of many greenstones, of the aporhyolites, and of other rocks that have suffered intense metamorphism. The quartzes are nearly always crossed by strain shadows and the fresh clear plagioclase by interrupted and bent twinning bars.

Here and there in the midst of this fine-grained groundmass are noticed lenticular and long narrow aggregates composed of grains of plagioclase that are much larger than the grains of this mineral occurring in the surrounding matrix. They look as though they might be the crushed remains of what were originally plagioclase phenocrysts.

Thus the microscopic study of these rocks tends to confirm the results of their field study. They were probably porphyritic lavas or intercalated flows that have suffered alteration as the result of intense pressure and movement. Their present composition suggests that they were originally quartz-porphyries or perhaps andesitic porphyrites. Whatever their original nature, their origin is different from that of the biotite-schists of the Marquette district.[1]

THE INTRUSIVE ROCKS.

The intrusives in the schists and gneissoid granites of the Basement Complex are granites, identical with the gneissoid granites above described, and greenstones. The former cut only the schists. They are probably apophyses from the larger granite masses. The greenstones cut the schists and the granites. They are similar in all respects to the greenstones in the sedimentary series, and thus are the youngest rocks in the district, with the exception of the horizontal Paleozoic sandstones and limestones that cap some of the higher hills.

The greenstones are all more or less altered diabases. In some the ophitic structure may be detected, but in most of them no traces of their original constituents nor of their structure remain. Nearly all are more or less schistose. The only evidence that the most schistose phases were once massive igneous rocks is in their composition and their occurrence in dike-like fissures. As the schistosity of these greenstones increases, the amount of their alteration also increases; there is a greater abundance of hornblende present in them and a greater quantity of quartz, until in the most schistose phases the rocks are now typical hornblende-schists.

One of the best examples of these greenstones occurs in the series of ledges extending in nearly a straight line for 6 miles from the southern portion of sec. 13, T. 42 N., R. 29 W., to the northeast corner of sec. 14, T. 42 N., R. 28 W. Except in its eastern ledges the rock constitutes bold,

[1] Mon. U. S. Geol. Survey, Vol. XXVIII, pp. 200–203.

rounded, bare knobs with almost perpendicular sides, usually situated in the midst of swamps. The main mass of the knobs is a rather fine-grained, slightly schistose, gray rock exhibiting the diabasic structure on weathered surfaces. On the south sides of the knobs the rock is much denser, and in most cases is much more highly schistose than the main rock mass.

Under the microscope these rocks present the usual features of schistose dike greenstones. They consist almost exclusively of hornblende, plagioclase, and quartz. The hornblende, which is the common yellowish-green variety, occurs in long plates and in columnar crystals, some of which are idiomorphic in cross section, and also in slender needles penetrating the quartz and feldspar. These two minerals form an aggregate between the larger hornblendes. The feldspar is mainly a calcium-soda plagioclase, though a small quantity of albite may also be present. It occurs as irregular grains embedded in a mosaic composed of rounded grains of the same feldspar and of quartz, and appears to be a new crystallization subsequent to that of the greater portion of the plagioclase. At any rate, a single large grain often fills the interstices between numbers of the mosaic grains and extinguishes uniformly over large areas. The magnetite in the rock is titaniferous. It occurs in little crystals and in small irregular grains that are often surrounded by a granular zone of leucoxene.

This rock may serve as a type of nearly all the other dike greenstones in the district under discussion. Some may be more schistose than this one, while a few may be more massive, but in general characteristics they are all similar. The more schistose rocks differ from the less schistose varieties simply in the possession of a greater amount of quartz and a greater quantity of what appears to be newly formed feldspar. Their greater schistosity is due to the more uniform elongation of their components.

The fine-grained greenstones found on the edges of the coarser-grained ones, and occasionally as independent dikes, are weathered diabases of the normal type.

COMPARISON OF THE STURGEON RIVER AND THE MARQUETTE CRYSTALLINE SERIES.

The Basement Complex in this area is essentially like that in the Marquette district, except that the altered tuffs so abundant in the northern area are absent from that now under discussion. The biotite-schists of the two

areas seem also to be different in origin, although this can not be stated with certainty, since the origin of the Marquette schists is not so clear as is that of the Sturgeon River schists. There is enough similarity between the crystalline series in the two areas to leave no doubt as to their practical identity. If the Marquette Basement Complex is Archean, the crystalline series underlying the conglomerates in the Sturgeon River tongue is also Archean.

THE ALGONKIAN TROUGH.

The sedimentary rocks comprised within the Sturgeon River Algonkian tongue may be separated into a conglomerate series and a dolomite series. The conglomerate series consists of schistose conglomerates, arkoses, quartzites, slates, and certain sericitic schists that are squeezed arkoses. The dolomite series embraces crystalline dolomites, a few thin beds of quartzite, a few breccias and conglomerates, and some slates.

It is possible that a third series, composed essentially of slates, also exists in the district, but if so it is not advisable to separate it from the dolomite series, since its exposures are very few in number, and the slates which comprise its main mass are so nearly like the slates belonging in the dolomite series that they can with difficulty be distinguished from these.

Associated with the sedimentary rocks are great masses of basic igneous ones. Some of these are unquestionably intrusive masses, as shown by their relations to the conglomerates, while others appear to be interleaved sheets. A very few, apparently bedded greenstones, on close examination seem to be composed of intermingled sedimentary and igneous material. These may be altered tuffs.

Nearly all the sedimentary as well as the igneous rocks embraced in the trough are schistose, and thus are sharply distinguished from the brown Potsdam sandstones and the Silurian limestones that here and there lie approximately horizontal on their upturned edges. The squeezing of the pre-Potsdam formations has been so intense that both conglomerates and dolomites have been forced into closely appressed folds, which in the conglomerates are for the most part apparently isoclinal. The strike of the latter rocks is nearly east and west, and their dip nearly perpendicular, except in one or two cases. The dolomites are less closely folded than the conglomerates. Their dips are much less steep, and their strike varies

considerably, except in the narrow eastern portion of the tongue, where it is approximately parallel to that of the conglomerate, i. e., a few degrees north of east.

RELATIONS BETWEEN THE CONGLOMERATE AND THE DOLOMITE SERIES AND CORRELATION WITH THE FELCH MOUNTAIN FRAGMENTALS.

The relations of the conglomerates to the dolomites are best shown by the distribution of their respective outcrops, as members of the two series are nowhere in contact. In the central portion of the tongue the conglomerate outcrops are limited to the district between the central granites and the southern area of the Basement Complex. The dolomites, on the other hand, are limited to the country north of the central granite. Its outcrops are found scattered over the northern tier of sections in T. 42 N., Rs. 28 W. and 29 W., and the southern tier of sections in T. 43 N., Rs. 28 W. and 29 W. Between them and the granite to the north is a belt of country devoid of exposures. It is heavily drift covered, consisting of sand plains and sand hills, from beneath which no ledges of any kind protrude. This barren belt measures about a half mile in width, in sec. 2, T. 42 N., R. 28 W., gradually increasing in width till it reaches the center of sec. 1 in T. 43 N., R. 29 W., where it opens out into the large Pleistocene area whose southeast edge is shown on the map (Pl. LI). In the eastern portion of the district the northern granites and the conglomerates approach each other, and the dolomite belt becomes very narrow, finally disappearing toward the east side of T. 42 N., R. 28 W.

The relative distribution of the conglomerate and dolomite ledges, when considered with reference to the triangular outline of the area embraced between the northern and the southern granite-schist complexes, suggests that the two formations constitute a western-pitching syncline with the dolomite in the center and the conglomerates with their associated beds on the two flanks. The conglomerates comprising the southern flank are well exposed, but those of the northern flank are not seen. They are believed to underlie the glacial deposits in the barren strip of country bordering the northern granites. The conglomerates, according to this view, are older than the dolomites.

Toward the center of the dolomite area, in the north half of sec. 6, T. 42 N., R. 28 W., and at a few places farther west, there are ferruginous

beds in the dolomite series. If these represent the upper portion of the dolomite formation, as is the case with similar rocks in the Felch Mountain range, it is clear that as we approach the center of the Sturgeon River tongue the rock beds met with are younger than those on its borders. This is in line with the supposition that the Sturgeon River tongue is a westward-pitching syncline.

The belief that the conglomerates are beneath the dolomites in the Sturgeon River area is further strengthened by the fact that the principal conglomerate in the Felch Mountain range is beneath a dolomite which is identical in character with the Sturgeon River dolomite. This conglomerate is regarded as the base of the Lower Menominee series in this district, with the dolomite above it, known as the Randville dolomite, immediately succeeding it. If the conglomerates and dolomites in the two districts are the same, the Sturgeon River rocks are Lower Menominee.

RELATIONS BETWEEN THE DOLOMITES AND CONGLOMERATES AND THE OVERLYING SANDSTONES.

At several places the conglomerates and dolomites are overlain by well-defined Lake Superior sandstone. The sandstone usually caps hills, on the lower slopes of which ledges of the underlying rocks appear. The contacts between the overlying sandstone and the underlying rocks are rarely seen, but the fact that the former are always horizontal, while the latter are always very steeply inclined, leaves no doubt that there is a strong unconformity between them.

THE CONGLOMERATE FORMATION.

The conglomerate formation comprises very much squeezed granitic conglomerates, arkoses, sericite-schists, quartzites, a few beds of banded rocks believed to consist largely of tuffaceous material (see pp. 485–487), and occasional beds of slates. Nearly all the members of the series are schistose, the arkoses in some cases passing into very well characterized sericite-schists. Occasionally the arkoses show obscure traces of ripple marking, and more frequently very well defined cross bedding.

All the rocks of this formation strike in a nearly uniform direction, N. 75°–84° E., and dip almost vertically. In one or two instances observed the dip is as low as 65°, but in most cases it varies between 85° N. and 85° S. The strike of the schistosity is approximately parallel to the strike

of the bedding, as is also the direction of the elongation of the pebbles so abundant in the conglomeratic layers.

From the slight changes in dip observed in the beds, as well as the great width of the formation in some places, it is evident that folding must exist. It is probable that in the wider portions of the area occupied by these rocks there are present two or more folds, so closely appressed that the beds on the opposite limbs can not be correlated. Hence they appear as members of a consecutive series of conformable members with a nearly uniform dip throughout. In the narrower portions of the area it can not be told whether more than one fold is present or not. In any event, the folding is practically isoclinal.

The ledges of the conglomerates and their associated beds occur in the southern portion of the Sturgeon River tongue throughout its entire extent. No exposures have been found north of the granite areas in the central and western portions of the tongue.

IMPORTANT EXPOSURES.

The arkoses, the sericite-schists, and the conglomeratic phases of the series can be best studied at the dam of the Sturgeon River near the northwest corner of sec. 17, T. 42 N., R. 28 W. Here they form a continuous ledge of well-bedded layers striking N. 83° E., and dipping 85° S., which measures at least 250 yards in width and 400 yards in length. (See Pl. LII.) The conglomerates are pink in color. They contain immense numbers of white quartz pebbles and bowlders, fewer and smaller ones of pink granite, and many fragments of red feldspar in a matrix composed of moderately coarse granite débris. All the fragments and pebbles in these rocks, as well as their matrix, show plainly the effects of pressure (Pl. LIII.) The matrix of all specimens is more or less schistose, and the coarse sand grains embedded in it are in many cases elongated in the direction of the schistosity. Most of the pebbles and bowlders in the conglomerate are also flat and parallel to the schistose plane. How far these phenomena are due to mashing, to rotation into parallel positions during flattening, and to original sedimentation, respectively, can not be determined in most cases, since the schistosity of the rock and the elongation of the pebbles are both approximately parallel to the bedding—i. e., the pebbles are nearly in the positions assumed by unequidimensional pebbles in a well-bedded conglomerate. In a few

MAP OF EXPOSURES

IN SEC. 7 AND IN PORTIONS OF SECS. 8, 17, AND 18, T. 42 N., R. 28 W., MICHIGAN

VICINITY OF DAM ON EAST BRANCH OF STURGEON RIVER

ARCHEAN — Gr.–Granite

ALGONKIAN
- A. Arkose
- Sl. Slate
- Q. Quartzite
- C. Conglomerate
- G.T. Greenstone tuffaceous

INTRUSIVE
- G. Greenstone
- G.S. Greenstone Schist

instances the schistosity may be seen to meet the bedding at a very acute angle. In this case the pebbles are usually arranged with their longer axes parallel to the schistosity, though there are always present a large number that lie parallel to the bedding planes.

In the least schistose phases of the rocks the pebbles are nearly round and the matrix possesses a well-defined fragmental texture, but in those beds in which the schistosity is more pronounced the matrix is sericitic and the pebbles are lenticular. The most completely schistose phases resemble augen-gneisses. In these the matrix is an almost typical sericite-schist. The quartz pebbles have been crushed and flattened into long narrow stringers or plates of quartz, some of which are continuous for long distances (6 or 7 inches), while others are broken into separate parts, which when rounded on their edges yield quartz lerses like the "augen" of so many augen-gneisses.[1]

The nonconglomeratic beds interstratified with the conglomerates are usually more completely schistose than the latter. The least schistose beds are arkoses. These often show ripple marking and current bedding. As the schistosity increases, the quantity of sericite present also increases, until in the most highly schistose phases sericite-schists result.

Some of the arkoses, as well as some of the finer-grained conglomerates, in addition to being schistose, are also foliated—i. e., they are built up of plates or leaves, along the planes between which they split very easily. When this is the case, the cleavage surfaces are covered by small scales of silvery mica. The foliation is so pronounced in many cases that the rocks are almost fissile.

Besides these rocks there are present near the dam great ledges of coarse and fine grained greenstone (see Pl. LII), whose relations to the sedimentary beds at first glance appear to be those of interleaved flows. Upon close inspection some of these masses disclose intrusive features. Although they almost invariably follow the bedding of the fragmental rocks, some of the greenstones can be seen to cut across the layers in such a manner as to leave no doubt of their intrusive character.

[1] The best examples of these extremely schistose conglomerates are not found in the exposures referred to above, but they are well developed along the line between secs. 11 and 12, T. 42 N., R. 29 W. Here the width of the series is but one-fourth mile, whereas the total width of these rocks and their associated greenstones near the dam measures a full mile.

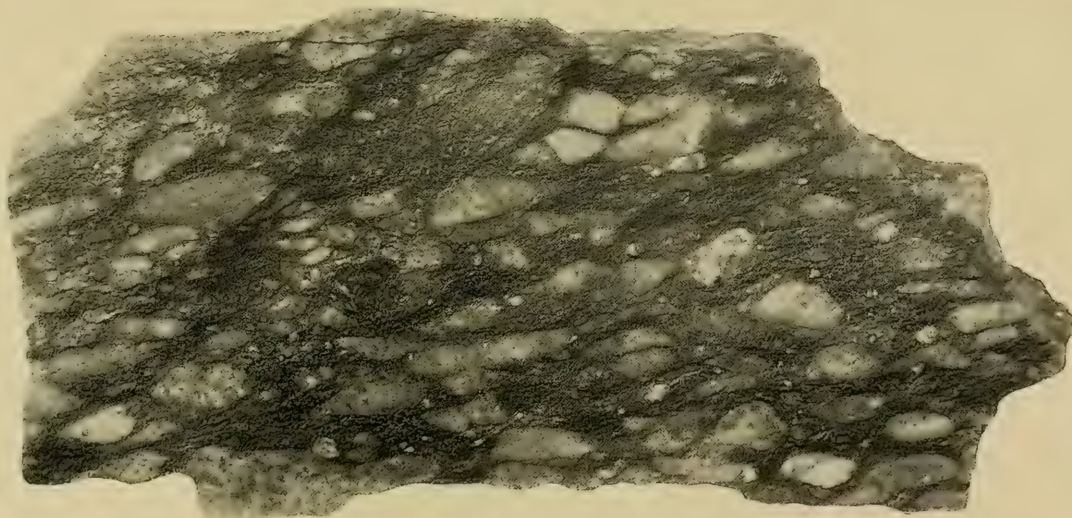
On the old road leading to the dam the conglomerates and arkoses are intruded by an altered diabase in a most complex way. To the north of the road is the great mass of the greenstone, within which are considerable areas of the conglomerate. Within the belt of conglomerate, on the other hand, are several bands of the eruptive rock which roughly follow the bedding of the sedimentary one, but which cut across it in a minor way.

At the contact of the main mass of greenstone and the conglomerate are numerous interlaminations of the two rocks, the greenstone having intruded the conglomerate along its bedding planes. At one place a dozen alternations of the two were noted within a foot. Moreover, for some distance from the greenstone the conglomerate appears to be impregnated with material from the intrusive, so that it has taken on a greenish tinge. This impregnation in one instance has gone on so far as to produce what is apparently a greenstone matrix containing separate pebbles from the conglomerate, the groundmass of the conglomerate having apparently been absorbed. The greenstone adjacent to the conglomerate is traversed by narrow pegmatite veins in various directions, some of the largest being not more than 2 inches in width. There is no evidence of a granitic intrusion, the pegmatites appearing clearly to be the result of an interaction between the basic igneous rock and the more acid fragmental one. At one place along the contact there is a belt of very coarse hornblendic material that is cut through and through by the pegmatite veins.

East and west of the dam for some distance are other ledges of conglomerate. They, however, as a rule, present no features different from those exhibited by the great ledge described above. In all, especially in those occurring in secs. 9 and 10, T. 42 N., R. 28 W., the interbanding of conglomeratic and nonconglomeratic layers is beautifully shown.

Near the north quarter post of sec. 11, T. 42 N., R. 28 W., the arkoses have a purple rather than a pink tinge. On cross fractures they are seen to be spangled with glistening black needles and plates of hornblende, which lie with their long axes in all azimuths. The little crystals appear to be more abundant in some layers than in others.

The best exposures of quartzite are found near the north quarter post of sec. 11, T. 42 N., R. 28 W., and at 1,300 paces W., 150 N., of the southeast corner of sec. 7, T. 42 N., R. 29 W. The rocks are black. They occur in beds varying in thickness from a few inches to several feet.



SCHIST CONGLOMERATE FROM DAM OF STURGEON RIVER, NEAR THE NORTHWEST CORNER OF SEC. 17, T. 42 N., R. 28 W.

Reproduced from Van Hise's Principles of North American Pre-Cambrian Geology, in Sixteenth Ann. Rept. U. S. Geol. Survey, Part I.

PETROGRAPHICAL DESCRIPTIONS.

As might naturally be expected, the least schistose of the arkoses and conglomerates exhibit the fewest evidences of alteration in the thin section. In addition to the pebbles in the conglomerates, these rocks consist of rounded and angular grains of quartz, microcline, orthoclase, and of various plagioclases, and a few of microperthite, embedded in a finer-grained aggregate of the same minerals, tiny flakes of green biotite and of colorless muscovite or sericite, a few plates of chlorite, particles and crystals of magnetite, and little nests and isolated grains of epidote, with occasionally some calcite. Many of the feldspar grains are altered into sericitic products, colored red by small particles of various iron oxides and by red earthy substances.

The composition and microstructure of the schistose arkoses and of the schistose matrices of the conglomerates vary greatly in different specimens, being determined largely by the original composition of the different beds and the amount of squeezing to which they have been subjected. No attempt will be made here to describe in detail all the changes suffered by these rocks; a simple statement of the tendency of these changes will be given.

The quartz pebbles in the moderately schistose conglomerates show plainly that they have been under great stresses. The smaller ones all exhibit undulatory extinction. The larger ones are sometimes peripherally granulated, and sometimes etched or corroded on their edges, as though they had suffered partial solution. By this process small portions of the original particles have been separated from them, and the dissolved silica has been redeposited among the grains of the surrounding matrix as secondary quartz. In their interiors many of the larger pebbles have been changed to a mosaic of differently oriented parts, which interlock so perfectly that they appear to have crystallized together.

The groundmass in which the pebbles lie is, in a few cases, a fragmental aggregate of quartz and several feldspars, with the addition of sericite and other crystallized components. In most cases, and in all in which schistosity is marked, no fragmental structure is noticeable. The groundmass is an interlocking mosaic of fairly large quartz grains that appear to have crystallized in situ, between which are smaller grains of the same

character, large and small spicules and plates of sericite, crystals of magnetite, and a few needles of chlorite and other secondary substances. Between these, again, is often a cement of what seems to be secondary quartz. The schistosity of the specimens is due to the arrangement of the sericite in approximately parallel positions, and to the elongation of the quartz grains in the same direction. The pink color of the rocks is produced by red earthy substances in the feldspars and in their decomposition products.

In the most schistose phases of the conglomerates the quartz pebbles have been mashed into plates, several of which join, end to end, forming sheets, which in the thin section appear as long narrow lines of variously oriented quartz grains, each of which is crossed by strain shadows.

The larger quartz grains in their matrices are broken into parts, and these parts are differently oriented with respect to one another. Other grains seem to have entirely recrystallized, for they are now made up exclusively of the same kind of interlocking quartzes as are present in the fine portions of the groundmass in which the coarse quartz grains are embedded. In the groundmass of these rocks sericite is very abundant, and feldspar is rare. From the proportions of these minerals present it would appear that the former has been derived largely from the latter. Biotite is also present in many specimens as small green flakes, but this mineral is not widely spread.

The conclusion from the study of the thin sections of the schistose conglomerates is that there has been a crystallization of new substances, principally quartz, sericite, biotite, and magnetite, from the materials of the original granitic sediments. Perhaps a portion of the crystallization was the result of alteration of the original components before squeezing took place. The larger portion, however, was accomplished under the influence of pressure. The result of the mashing and recrystallization is a schist, which between crossed nicols has the aspect of a typical crystalline schist, but which in natural light exhibits its conglomeratic nature in the presence of the large quartz lenses, with the outlines of flattened pebbles, in a fine-grained groundmass.

The pink arkoses differ from the conglomerates simply in the absence from them of the pebbles. The schistose varieties are similar in every respect to the schistose groundmass of the squeezed conglomerates. Both in the hand specimen and in the thin section the schistose arkoses exhibit striking resemblances to muscovitic gneisses.

The purple arkoses differ from the pink ones just described in containing chlorite and hornblende, and in addition some apparently newly formed feldspar, notably a feldspar with the microcline twinning. As a rule, these rocks are more feldspathic than the matrices of the conglomerates, and they contain much less quartz. The larger grains of both quartz and feldspar are corroded as if partially dissolved. They have lost their smooth, rounded contours of sand grains, and now possess irregular jagged ones, which, however, are not due to secondary enlargements.

The characteristic components of these rocks are the chlorite and the hornblende. The former mineral is present in plates intermingled with grains of epidote, while the hornblende is in dark-green or light-green plates, and in acicular or columnar crystals that are idiomorphic in cross section. The crystals are distributed indiscriminately through the rocks, with their longer axes lying in all azimuths. They were evidently formed after the squeezing that made the rock schistose. The plates, moreover, include within themselves such great numbers of the other components of the rock that their parts often appear to be independent. Under crossed nicols, however, many of these apparently independent plates are discovered to polarize together. No evidence is present in any of the sections as to the source of the material that gave rise to the hornblende. The fact, however, that all of the hornblendic rocks are banded, that some layers are rich in amphibole while others are completely devoid of this mineral, suggests the notion that the hornblendic schistose arkoses consist partly of sedimentary and partly of tuffaceous materials. As we shall see later, this origin is ascribed with more confidence to some very peculiar rocks to be discussed later.

Crushing effects are noticed in some of the hornblendic arkoses, but their present condition appears to be due more to chemical changes produced in them than by mechanical action. The chemical changes were no doubt superinduced by the mashing, but this can only be inferred from the fact that they are more pronounced in the schistose phases of the rocks than in those phases in which the schistosity is poorly developed.

THE DOLOMITE FORMATION.

The dolomite formation comprises, as has been stated, both dolomitic limestones and calcareous slates, and occasionally quartzites, sandstones,

and conglomeratic and brecciated beds. As a rule, exposures are small and scattered. Their distribution has already been described. All ledges observed may be seen by reference to the map (Pl. LI).

IMPORTANT EXPOSURES.

Good exposures of the dolomites occur in the NW. ¼ sec. 6, T. 42 N., R. 28 W. The ledge nearest the northwest corner of the section is a hard flesh-colored dolomitic marble, containing here and there little quartz grains. This is cut by joints, and is traversed by small chert bands. The bedding is more or less contorted, but its general strike is N. 45° E., and its dip is 45° NW. About one-fourth mile east of this ledge is a small, bare knoll, composed of interlaminated pink marbles, conglomerates, red sandstones, and red slates, varying in thickness from a few inches to a foot or more. The conglomerate consists of marble pebbles and slate and chert fragments in a calcareous quartzitic matrix. The strikes and dips are uniform throughout the ledge, the former being nearly east and west and the latter 45° S. The difference in dip of the beds of these two exposures indicates plainly the presence in this place of a little westward-pitching anticline.

Other prominent exposures of the dolomite series are in the NW. ¼ sec. 1, T. 42 N., R. 29 W., and in the SE. ¼ sec. 35, T. 43 N., R. 29 W. In the first-named locality is a high, bare knob, and a cluster of small ledges, in which dolomites, conglomerates, and slates are all well exposed. The dolomites, for the greater part, are massive pink marbles crossed by joint planes. In places the rocks take on a greenish-yellow tinge, and become schistose. At 1,500 paces N., 1,930 W., of the southeast corner of sec. 1, T. 42 N., R. 29 W., the dolomite forms a well-defined bed, striking N. 45° E. and dipping 70° SE. Above this, to the southeast, is a bed of coarse-grained granitic sandstone or quartzite, which in turn is over-lain by beds of gray quartzite alternating with thin slates and fine-grained conglomerates. Farther south is a ridge of well-bedded, fine-grained quartzite and bluish-gray slate, the individual layers being usually less than one-half inch in thickness. This rock grades into a gray schistose dolomite, and the whole quartzite-slate series strikes N. 75° E. and dips 63° S. The exposures in section 35 are almost pure marbles, in which no traces of bedding have been detected.

PETROGRAPHICAL DESCRIPTION.

In thin section the marbles appear as very close-grained aggregates of calcite and dolomite, usually untwinned, but occasionally twinned in the ordinary manner of these minerals. Here and there among the carbonates are rounded quartz grains, but the greater portion of this mineral appears to have crystallized in situ between the calcite and dolomite individuals.

All the marbles are of the same general character. They differ only in the quantity of silica present and in the presence or absence of the tiny dust grains producing the color. The schistose varieties owe their schistosity to the elongation of their components.

The quartzites and slates interbedded with the marbles possess no unusual characters. They are similar to the corresponding rocks interstratified with the Marquette dolomites. The conglomerates interstratified with the dolomites, slates, and quartzites are of two kinds. One is composed of marble and slate fragments cemented by quartzite, and the other of small granite pebbles embedded in granite sand. The latter are evidently composed of the detritus of the granites underlying the dolomite series, while the marble-bearing conglomerates, or perhaps more properly breccias, are interformational beds conformable with the beds below them, and also with those above. They are similar in every respect to the interbedded breccias in the Kona dolomites on the Marquette range.

SLATES AND SANDSTONES ON THE STURGEON RIVER.

The rocks in the SW. $\frac{1}{4}$ sec. 34, where the road to Sagola crosses the Sturgeon River, are placed in the dolomite formation, although they differ somewhat from that portion of the series described. These rocks are white calcareous sandstones, that look very much like the Potsdam sandstone where it overlies limestones, and a light-green slate, which near joint planes and other cracks has a light purple color. According to Dr. J. M. Clements, who visited the spot, the slate overlies the sandstone. "The river," he writes in his notebook, "gives a section through these rocks, and makes the strike seem to be N. 35° W., dip 50° N. It appears to me, however, that the true strike is about N. 85° E., and dip 40° S." If these rocks belong to the marble series, they constitute its upper part. The slate closely resembles some of the slates in the Kona dolomite formation of the

Marquette range. It is a very fine grained rock composed of very small splinters of quartz, flakes of sericite, and a few of chlorite.

THE IGNEOUS ROCKS.

The igneous rocks associated with the sedimentary beds in the Sturgeon River tongue are all greenstones in composition. Many of them are unquestionably intrusive; a few may be tuffaceous.

The intrusive greenstones do not differ essentially from those cutting the Basement Complex. Some of them are in the form of small bosses. Others are clearly dikes, though for the most part these dikes follow the bedding of the sedimentary rocks. Still others may be intrusive sheets. The rocks regarded as possibly tuffaceous are distinctly banded. Some are made up of alternate bands of dark and light shades. The darker bands consist principally of a schistose greenstone, and the lighter ones principally of arkose or granitic sandstone. These rocks are well bedded, apparently constituting a definite portion of the conglomerate series near its lower horizon.[1]

THE INTRUSIVE GREENSTONES.

The intrusive greenstones are usually fairly massive rocks, with a dark bluish-green color and a moderately fine grained texture. On their edges they often pass into schistose phases, presenting the structure and appearance of chlorite-schists. A very typical schist of this character occurs on the southern edge of the great greenstone mass 1,525 to 1,600 paces north and 300 to 400 west of the southeast corner of sec. 18, T. 42 N., R. 28 W. In the hand specimen the rock appears to be a well-characterized chlorite-schist, spangled with plates of a light-colored muscovite measuring 1.5 to 2 mm. in diameter.

The intrusive character of some of the greenstones is clearly shown by the fact that they occur immediately on the strike of the conglomerate bands, and often cutting across them, as is the case at 300 paces east of the northwest corner of sec. 17, T. 42 N., R. 28 W. (see Pl. LII), and at 400 paces south, 100 west, of this same corner.

PETROGRAPHICAL DESCRIPTION.

The greenstones intrusive in the Algonkian sediments are not essentially different from those cutting the members of the Basement Complex.

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[1] See Van Hise's Notebook 184, pp. 21–23.

They differ from the latter in containing, as a rule, less quartz and a very much greater abundance of epidote. The epidote is all secondary, as is also the quartz, so that the only noticeable difference between the two sets of greenstones is dependent upon differences in the nature of their alteration, which in turn are probably the results of differences in environment. Both sets of greenstones have been squeezed, but those in the Basement Complex are associated with crystalline schists, while those in the Algonkian series are associated with fragmental beds.

In addition to hornblende, plagioclase, epidote, and a little quartz, almost all the later greenstones contain biotite, small crystals of magnetite, and irregular grains of ilmenite or of a titaniferous magnetite. Their structure is schistose through the arrangement of the larger hornblendes and biotites and the elongation of the feldspar grains in approximately parallel directions. As a rule, their thin sections present no unusual features. They all show dirty green hornblende plates, greenish-brown biotite flakes, magnetite crystals, etc., embedded in a mass of irregular grains of decomposed plagioclase, the principal decomposition product of the feldspar being in almost all cases epidote.

Often the proportion of epidote present is very great. It occurs as colorless crystals and grains scattered through the hornblende, and as light-yellow plates and grains embedded in the mass of altered plagioclase. In the rock at 500 paces east, 125 north, of the southwest corner of sec. 8, T. 42 N., R. 28 W. (Pl. LII), the replacement of the plagioclase by epidote has proceeded so far that no trace of the feldspar can be discovered. In the hand specimen the rock is seen to be a massive mixture of black glistening hornblende crystals in a yellowish-green groundmass possessing a sugary texture. In the thin section the hornblende is present as bluish-green plates that are often idiomorphic in cross section. The groundmass in which they lie is composed of epidote and quartz. The epidote is in large yellowish-green irregularly-outlined plates, including particles of magnetite and small rounded quartz grains. Most of the quartz is in isolated grains between the epidote plates and in little nests of interlocking grains. Small magnetite granules are scattered everywhere throughout the section, through all of the components indiscriminately

The coarser greenstones show plainly in the hand specimen the ophitic structure, even where the rocks are schistose. In the section this structure

is often obscured by the abundance of decomposition products. Under low powers of the microscope, however, it can nearly always be detected. In a few of the finer-grained varieties, phenocrysts of plagioclase are occasionally met with. They are clouded by inclusions of biotite flakes and shreds of hornblende and by tiny particles of a kaolinitic or sericitic mineral. From their composition and structure, it is clearly evident that the intrusive greenstones, whether massive or schistose, are altered phases of diabase or of diabase-porphyrite.

The dark-green chlorite-schist referred to as occurring in the edge of one of the greenstone masses is a chloritic biotite-schist spangled with large flakes of a light-colored mica. The rock consists of biotite, chlorite, muscovite, quartz, and rutile. The biotite is in broad thin plates, arranged approximately parallel, and embedded in a mass of chlorite, the greater portion of which is a greenish-brown variety that looks as though it may have been derived from hornblende. A smaller portion of the chlorite is in light-green plates, like the chlorite so frequently found in chlorite-schist. The quartz is in small rounded grains exhibiting strain shadows, scattered here and there through the chlorite and between the biotite plates. It is much more abundant in some portions of the rock than in others, forming bands rich in quartz, between others in which very little of this mineral is present. The rutile is in large quantity. It constitutes large greenish-yellow grains. Some of these are rounded forms, others are prismatic crystals measuring 0.08 mm. to 0.12 mm. in length, while still others are clearly defined elbow twins. They occur everywhere throughout the slide, but are rare in the quartz. They are most abundant in the chlorite and in the large plates of light-colored mica that have been mentioned as characteristic features of the hand specimens. These have all the properties of muscovite. They lie indiscriminately among the other components, irrespective of the schistosity of the rock, and contain very few inclusions, with the exception of the rutile grains. The lines of biotite, to the arrangement of which the rock owes its schistosity, do not bend around the muscovite as they do around the eyes in an augen-gneiss, but they continue their courses up to the edge of the muscovite grain, and there abruptly stop. From these facts it is clear that the muscovites have originated since the rock containing them was rendered schistose. As in the case of many other secondary minerals, it appears that these were produced from the components of the

schist by a process which resulted in the absorption of all of them except rutile. The process may have been connected with contact action, but no evidence in favor of this supposition has been obtained.

There are a few other types of greenstone occasionally met with among the dike and other intrusive forms of the district, but they do not differ in any marked degree from those described, except that some are quite schistose. One or two of these contain oval aggregates of epidote, plagioclase, and quartz, that may represent inclusions of foreign rocks. They are now, however, so much altered that it is difficult to determine their character with any degree of certainty.

The rock of one or two other exposures in the area underlain mainly by the conglomerates deserves mention before the banded greenstones are discussed. The rock referred to is a heavy, lustrous, black schist that resembles in many respects a hornblende-schist. On fresh fractures across the schistosity parallel lines, darker than the main mass of the rock, may be easily detected. These are the edges of cleavage planes, whose surfaces are coated with brassy yellow mica plates. In thin section these rocks differ very little from the schistose greenstones referred to above. They consist of a heterogeneous schistose mass of green hornblende, cloudy plagioclase, quartz, epidote, chlorite, and magnetite. Biotite flakes are met with occasionally, but they are by no means common, except on the cleavage surfaces. Rocks of this class have not only been made schistose by squeezing, but they have also suffered shearing along what are now the cleavage planes. They are almost identical in microscopic and macroscopic features with the hornblende-schists in the Basement Complex.

THE BANDED GREENSTONES.

Distinctly banded rocks, composed partly of basic material with the composition of greenstone, form a well-defined hillock in sec. 17, T. 42 N., R. 28 W., about 250 paces north of the west quarter post of this section, and a group of outcrops on the east bank of the Sturgeon River, immediately west of this point.

The rocks in question are banded in mediumly coarse-grained dark bands, containing large quantities of green hornblende, and in fine-grained lighter ones, that resemble in the hand specimen bluish-black quartzites or cherts. In some bands there are large lenticules of white quartz, that show

plainly on weathered surfaces, like the flattened pebbles in a squeezed conglomerate or the drawn-out parts of quartzose layers in a mashed bedded rock. These bands, though not very well defined, run continuously for long distances, and strike and dip conformably with the conglomerate beds exposed 200 paces to the north.

PETROGRAPHICAL DESCRIPTION.

In the thin section the lighter-colored layers of these rocks are seen to be composed of very irregularly outlined and rounded quartz grains, cemented by a mass of finer quartzes and small grains of zoisite, little clumps of chlorite, some decomposed feldspar, and particles of magnetite. Occasionally a plate of yellowish epidote occurs in the midst of this aggregate, and scattered here and there through it are large plates of green hornblende with the cellular structure so common to secondary minerals. These hornblendes lie irregularly in the slide, and include grains of all the other components. The quartz grains are small and are independently oriented, but frequently little groups of them, with the outlines of sand grains, are met with. There is little evidence of schistosity in these layers, but they exhibit a banding produced by the alternation of coarser and finer constituents. In the darker layers the proportion of hornblende is much greater than it is in the lighter ones. Indeed, some bands consist almost exclusively of large cellular plates and radial aggregates of plates of this mineral, only the small interstitial spaces between the large amphiboles being filled with an aggregate of quartz-zoisite, small hornblende needles, and magnetite. In some sections biotite is also present. It occurs most abundantly in the quartz-zoisite aggregate, filling the interstitial spaces between the amphiboles, but is present also as inclusions in this latter mineral. Some of the biotite in the hornblende appears to grade into its host, and certain portions of the amphibole possesses the brown color of the mica, with the optical properties of the hornblende. The large amphiboles are evidently the youngest components in the rocks, though they were plainly produced before the schistosity. In those layers in which the schistosity is strongly marked this structure is produced mainly by the parallel arrangement of the biotite and the small amphibole needles and plates in the quartzose aggregate. The larger cellular hornblendes lie across the schistose planes, and when they do so, the lines of biotite and of small amphiboles pass

around them exactly as they would do were the large hornblendes present before the rock was squeezed. Sometimes the amphibole masses that form so large a proportion of the schistose bands are single crystals, sometimes they are fragments of crystals, and at other times they are groups of radiating crystals. The magnetite is very much more abundant in the hornblendes than in the surrounding quartz aggregate, sometimes being confined exclusively to this mineral, as though it were one of the products (the hornblende being the other) resulting from the decomposition of some original constituent, probably augite. Little particles of hematite, on the other hand, are abundantly disseminated through the quartzose aggregate, and are practically absent from the hornblende. Much of it appears to have been derived from magnetite.

The evidence derived from the microscopic study of sections of these banded rocks, so far as it relates to their origin, is disappointing. The quartzose layers are, in all probability, sedimentary. The hornblendic layers, however, differ from these so much in composition that their material must have had a different source. It is possible that the quartzose layers represent sediments derived from the granitic portions of the Basement Complex, while the hornblendic layers represent sediments derived from the basic portions of the Basement Complex; or, it may be that the acid layers have the origin ascribed to them, while the basic ones are mixed sediments and basic tuffs. The sections of the dark layers of these rocks resemble so strongly the sections of the basic layers in the Clarksburg series of mixed tuffs and sediments in the Marquette district that the writer is inclined to regard the rocks as composed partly of tuffaceous material. On the other hand, the banded rocks occur so close to the boundary between the sedimentary area and the Basement Complex, which near this boundary is composed mainly of basic schists, that it would seem but natural that they should contain large quantities of basic material derived from these schists. The original structure of the layers has been so completely destroyed by mashing that it can not give any evidence as to the nature of the beds. We are therefore compelled to rely entirely upon their composition to aid us in discovering their origin. This indicates simply that much of their material was derived either from volcanic ashes or from the débris washed from the basic portions of the Basement Complex.

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ADVERTISEMENT.

[Monograph XXXVI.]

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"The publications of the Geological Survey shall consist of the annual report of operations, geological and economic maps illustrating the resources and classification of the lands, and reports upon general and economic geology and paleontology. The annual report of operations of the Geological Survey shall accompany the annual report of the Secretary of the Interior. All special memoirs and reports of said Survey shall be issued in uniform quarto series if deemed necessary by the Director, but otherwise in ordinary octavos. Three thousand copies of each shall be published for scientific exchanges and for sale at the price of publication; and all literary and cartographic materials received in exchange shall be the property of the United States and form a part of the library of the organization: And the money resulting from the sale of such publications shall be covered into the Treasury of the United States."

Except in those cases in which an extra number of any special memoir or report has been supplied to the Survey by special resolution of Congress or has been ordered by the Secretary of the Interior, this office has no copies for gratuitous distribution.

ANNUAL REPORTS.

I. First Annual Report of the United States Geological Survey, by Clarence King. 1880. 8°. 79 pp. 1 map.—A preliminary report describing plan of organization and publications.

II. Second Annual Report of the United States Geological Survey, 1880–'81, by J. W. Powell. 1882. 8°. lv, 588 pp. 62 pl. 1 map.

III. Third Annual Report of the United States Geological Survey, 1881–'82, by J. W. Powell. 1883. 8°. xviii, 564 pp. 67 pl. and maps.

IV. Fourth Annual Report of the United States Geological Survey, 1882–'83, by J. W. Powell. 1884. 8°. xxxii, 473 pp. 85 pl. and maps.

V. Fifth Annual Report of the United States Geological Survey, 1883–'84, by J. W. Powell. 1885. 8°. xxxvi, 469 pp. 58 pl. and maps.

VI. Sixth Annual Report of the United States Geological Survey, 1884–'85, by J. W. Powell. 1885. 8°. xxix, 570 pp. 65 pl. and maps.

VII. Seventh Annual Report of the United States Geological Survey, 1885–'86, by J. W. Powell. 1888. 8°. xx, 656 pp. 71 pl. and maps.

VIII. Eighth Annual Report of the United States Geological Survey, 1886–'87, by J. W. Powell. 1889. 8°. 2 pt. xix, 474, xii pp., 53 pl. and maps; 1 prel. leaf, 475–1063 pp., 54–76 pl. and maps.

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X. Tenth Annual Report of the United States Geological Survey, 1888–'89, by J. W. Powell. 1890. 8°. 2 pt. xv, 774 pp., 98 pl. and maps; viii, 123 pp.

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XIV. Fourteenth Annual Report of the United States Geological Survey, 1892–'93, by J. W. Powell. 1893. 8°. 2 pt. vi, 321 pp., 1 pl.; xx, 597 pp., 74 pl. and maps.

XV. Fifteenth Annual Report of the United States Geological Survey, 1893–'94, by J. W. Powell. 1895. 8°. xiv, 755 pp., 48 pl. and maps.

XVI. Sixteenth Annual Report of the United States Geological Survey, 1894–'95, Charles D. Walcott, Director. 1895. (Part I, 1896.) 8°. 4 pt. xxii, 910 pp., 117 pl. and maps; xix, 598 pp., 43 pl. and maps; xv, 646 pp., 23 pl.; xix, 735 pp., 6 pl.

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XVIII. Eighteenth Annual Report of the United States Geological Survey, 1896–'97, Charles D. Walcott, Director. 1897. (Parts II and III, 1898.) 8°. 5 pt. in 6 vol. 1–440 pp., 4 pl. and maps; i–v,

1–653 pp., 105 pl. and maps; i–v, 1–861 pp., 118 pl. and maps; i–x, 1–756 pp., 102 pl. and maps; i–xii, 1–642 pp., 1 pl.; 643–1400 pp.

XIX. Nineteenth Annual Report of the United States Geological Survey, 1897–'98, Charles D. Walcott, Director. 1898. 8°. 6 pt. in 7 vol.

MONOGRAPHS.

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The map sheets represent a great variety of topographic features, and with the aid of descriptive text they can be used to illustrate topographic forms. This has led to the projection of an educational series of topographic folios, for use wherever geography is taught in high schools, academies, and colleges. Of this series the first folio has been issued, viz:

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GEOLOGIC ATLAS OF THE UNITED STATES.

The Geologic Atlas of the United States is the final form of publication of the topographic and geologic maps. The atlas is issued in parts, progressively as the surveys are extended, and is designed ultimately to cover the entire country.

Under the plan adopted the entire area of the country is divided into small rectangular districts (designated *quadrangles*), bounded by certain meridians and parallels. The unit of survey is also the unit of publication, and the maps and descriptions of each rectangular district are issued as a folio of the Geologic Atlas.

Each folio contains topographic, geologic, economic, and structural maps, together with textual descriptions and explanations, and is designated by the name of a principal town or of a prominent natural feature within the district.

Two forms of issue have been adopted, a "library edition" and a "field edition." In both the sheets are bound between heavy paper covers, but the library copies are permanently bound, while the sheets and covers of the field copies are only temporarily wired together.

Under the law a copy of each folio is sent to certain public libraries and educational institutions. The remainder are sold at 25 cents each, except such as contain an unusual amount of matter, which are priced accordingly. Prepayment is obligatory. The folios ready for distribution are listed below.

No.	Name of sheet.	State.	Limiting meridians.	Limiting parallels.	Area, in square miles.	Price, in cents.
1	Livingston	Montana	110°–111°	45°–46°	3,354	25
2	Ringgold	Georgia Tennessee	85°–85° 30′	34° 30′–35°	980	25
3	Placerville	California	120° 30′–121°	38° 30′–39°	932	25
4	Kingston	Tennessee	84° 30′–85°	35° 30′–36°	969	25
5	Sacramento	California	121°–121° 30′	38° 30′–39°	932	25
6	Chattanooga	Tennessee	85°–85° 30′	35°–35° 30′	975	25
7	Pikes Peak (out of stock)	Colorado	105°–105° 30′	38° 30′–39°	932	25
8	Sewanee	Tennessee	85° 30′–86°	35°–35° 30′	975	25
9	Anthracite-Crested Butte	Colorado	106° 45′–107° 15′	38° 45′–39°	465	50
10	Harpers Ferry	Virginia West Virginia Maryland	77° 30′–78°	39°–39° 30′	925	25

No.	Name of sheet.	State.	Limiting meridians.	Limiting parallels.	Area, in square miles.	Price, in cents.
11	Jackson	California	120° 30′-121°	38°-38° 30′	938	25
12	Estillville	Virginia Kentucky Tennessee	82° 30′-83°	36° 30′-37°	957	25
13	Fredericksburg	Maryland Virginia	77°-77° 30′	38°-38° 30′	938	25
14	Staunton	Virginia West Virginia	79°-79° 30′	38°-38° 30′	938	25
15	Lassen Peak	California	121°-122°	40°-41°	3, 634	25
16	Knoxville	Tennessee North Carolina	83° 30′-84°	35° 30′-36°	925	25
17	Marysville	California	121° 30′-122°	39°-39° 30′	925	25
18	Smartsville	California	121°-121° 30′	39°-39° 30′	925	25
19	Stevenson	Alabama Georgia Tennessee	85° 30′-86°	34° 30′-35°	980	25
20	Cleveland	Tennessee	84° 30′-85°	35°-35° 30′	975	25
21	Pikeville	Tennessee	85°-85° 30′	35° 30′-36°	969	25
22	McMinnville	Tennessee	85° 30′-86°	35° 30′-36°	969	25
23	Nomini	Maryland Virginia	76° 30′-77°	38°-38° 30′	938	25
24	Three Forks	Montana	111°-112°	45°-46°	3, 354	50
25	Loudon	Tennessee	84°-84° 30′	35° 30′-36°	969	25
26	Pocahontas	Virginia West Virginia	81°-81° 30′	37°-37° 30′	951	25
27	Morristown	Tennessee	83°-83° 30′	36°-36° 30′	963	25
28	Piedmont	Virginia Maryland West Virginia	79°-79° 30′	39°-39° 30′	925	25
29	Nevada City: Nevada City Grass Valley Banner Hill	California	121° 00′ 25″-121° 03′ 45″ 121° 01′ 35″-121° 05′ 04″ 120° 57′ 05″-121° 00′ 25″	39° 13′ 50″-39° 17′ 16″ 39° 10′ 22″-39° 13′ 50″ 39° 13′ 50″-39° 17′ 16″	11. 65 12. 09 11. 65	50
30	Yellowstone National Park: Gallatin Canyon Shoshone Lake	Wyoming	110°-111°	44°-45°	3, 412	75
31	Pyramid Peak	California	120°-120° 30′	38° 30′-39°	932	25
32	Franklin	Virginia West Virginia	79°-79° 30′	38° 30′-39°	932	25
33	Briceville	Tennessee	84°-84° 30′	36°-36° 30′	963	25
34	Buckhannon	West Virginia	80°-80° 30′	38° 30′-39°	932	25
35	Gadsden	Alabama	86°-86° 30′	34°-34° 30′	986	25
36	Pueblo	Colorado	104° 30′-105°	38°-38° 30′	938	50
37	Downieville	California	120° 30′-121°	39° 30′-40°	919	25
38	Butte Special	Montana	112° 29′ 30″-112° 36′ 42″	45° 59′ 28″-46° 02′ 54″	22. 80	50
39	Truckee	California	120°-120° 30′	39°-39° 30′	925	25
40	Wartburg	Tennessee	84° 30′-85°	36°-36° 30′	963	25
41	Sonora	California	120°-120° 30′	37° 30′-38°	944	25
42	Nueces	Texas	100°-100° 30′	29° 30′-30°	1, 035	25
43	Bidwell Bar	California	121°-121° 30′	39° 30′-40°	918	25
44	Tazewell	Virginia West Virginia	81° 30′-82°	37°-37° 30′	950	25
45	Boise	Idaho	116°-116° 30′	43° 30′-44°	864	25
46	Richmond	Kentucky	84°-84° 30′	37° 30′-38°	944	25
47	London	Kentucky	84°-84° 30′	37°-37° 30′	950	25
48	Tenmile District Special	Colorado	106° 8′-106° 16′	39° 22′ 30″-39° 30′ 30″	55	25
49	Roseburg	Oregon	123°-123° 30′	43°-43° 30′	871	25
50	Holyoke	Massachusetts Connecticut	72° 30′-73°	42°-42° 30′	885	25

STATISTICAL PAPERS.

Mineral Resources of the United States [1882], by Albert Williams, jr. 1883. 8°. xvii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1883 and 1884, by Albert Williams, jr. 1885. 8°. xiv, 1016 pp. Price 60 cents.

Mineral Resources of the United States, 1885. Division of Mining Statistics and Technology. 1886. 8°. vii, 576 pp. Price 40 cents.

Mineral Resources of the United States, 1886, by David T. Day. 1887. 8°. viii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1887, by David T. Day. 1888. 8°. vii, 832 pp. Price 50 cents.

Mineral Resources of the United States, 1888, by David T. Day. 1890. 8°. vii, 652 pp. Price 50 cents.

Mineral Resources of the United States, 1889 and 1890, by David T. Day. 1892. 8°. viii, 671 pp. Price 50 cents.

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Mineral Resources of the United States, 1893, by David T. Day. 1894. 8°. viii, 810 pp. Price 50 cents.

On March 2, 1895, the following provision was included in an act of Congress:

"*Provided*, That hereafter the report of the mineral resources of the United States shall be issued as a part of the report of the Director of the Geological Survey."

In compliance with this legislation the following reports have been published:

Mineral Resources of the United States, 1894, David T. Day, Chief of Division. 1895. 8°. xv, 646 pp., 23 pl.; xix, 735 pp., 6 pl. Being Parts III and IV of the Sixteenth Annual Report.

Mineral Resources of the United States, 1895, David T. Day, Chief of Division. 1896. 8°. xxiii, 542 pp., 8 pl. and maps; iii, 543-1058 pp., 9-13 pl. Being Part III (in 2 vols.) of the Seventeenth Annual Report.

Mineral Resources of the United States, 1896, David T. Day, Chief of Division. 1897. 8°. xii, 642 pp., 1 pl.; 643-1400 pp. Being Part V (in 2 vols.) of the Nineteenth Annual Report.

Mineral Resources of the United States, 1897, David T. Day, Chief of Division. 1898. 8°. viii, 651 pp., 11 pl.; viii, 706 pp. Being Part VI (in 2 vols.) of the Nineteenth Annual Report.

The money received from the sale of the Survey publications is deposited in the Treasury, and the Secretary of that Department declines to receive bank checks, drafts, or postage stamps; all remittances, therefore, must be by MONEY ORDER, made payable to the Director of the United States Geological Survey, or in CURRENCY—the exact amount. Correspondence relating to the publications of the Survey should be addressed to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

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Author.

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